

UNIVERSITÉ DE MONTRÉAL

DÉTECTION DIRECTE D'UN GISEMENT DE SULFURES MASSIFS
VOLCANOGÈNES PAR SISMIQUE RÉFLEXION

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DÉTECTION DIRECTE D'UN GISEMENT DE SULFURES MASSIFS
VOLCANOGÈNES PAR SISMIQUE RÉFLEXION

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RÉSUMÉ

L'objectif de cette étude est d'évaluer l'applicabilité de la sismique réflexion 3D, couramment utilisée en exploration pétrolière, à la prospection pour les gisements profonds de type sulfures massifs volcanogènes (SMV). Le camp minier de Matagami, situé dans la ceinture de roches vertes de l'Abitibi, se prête bien pour cette étude puisque le pendage des unités lithologiques est modéré ($\sim 45^\circ$) et que la plupart des contacts peuvent être suivis sur plusieurs dizaines de kilomètre. Les études pétrophysiques en forage et sur des échantillons ont démontré que les contacts rhyolite-gabbro étaient susceptibles de générer de fortes réflexions sismiques. La réflectivité des contacts lithologiques du camp minier de Matagami permet donc aux méthodes de sismique réflexion de les cartographier à des profondeurs excédant 3 km. L'analyse d'échantillons du gisement d'Isle-Dieu et les diagaphies dans des forages ayant recoupé le gisement de Bell Allard ont aussi montré que les sulfures massifs et semi-massifs pouvaient être réflectifs. En particulier, les sulfures riches en minéraux de forte impédance acoustique (i.e. pyrite et magnétite) peuvent générer, si leur taille est suffisamment grande, des réflexions d'amplitude élevée. Un levé sismique 2D au-dessus du gisement Bell Allard a permis d'identifier une anomalie géophysique associée au dépôt. Cependant, à cause de la possibilité de réflexion provenant du côté de la ligne sismique ("side-swipe"), un profil sismique vertical (PSV) a été nécessaire pour démontrer que le gisement de Bell Allard était réflectif. Le levé PSV a enregistré une forte réflexion de l'onde de compression et une conversion en onde de cisaillement at-

tribuable à la présence des sulfures massifs. Une étude de modélisation a été réalisée en utilisant la géométrie de trou d'exploration existant afin d'évaluer les PSV comme outil d'exploration. Les amplitudes des sismogrammes synthétiques générés pour ce modèle étant généralement faibles et ce, indépendamment de la position du point de tir, cette méthode n'est pas recommandée pour assister l'exploration profonde dans le camp de Matagami.

Un levé 3D a été réalisé en 1996 pour couvrir une région de 20 km² incluant le gisement de Bell Allard situé à 1 km de profondeur. Les objectifs du levé étaient d'identifier la réponse sismique du gisement de Bell Allard et de cartographier les principaux contacts lithologiques en profondeur. La signature sismique du gisement de Bell Allard se présente comme une zone de fortes amplitudes sismiques d'une largeur de 100 m. Le gisement est situé au-dessus d'une anomalie d'amplitude plus grande qui est interprétée comme un sill de gabbro ou la cheminée d'altération du dépôt. L'étude montre aussi que la profondeur de la principale cible d'exploration (la Tuffite Clé) peut être déterminée sur une grande partie du levé sismique et que la limite sud-ouest de l'interprétation définit la position d'une faille importante (faille Daniel). D'autre part, l'orientation et le pendage d'une faille synvolcanique ont été déterminés à partir de l'analyse d'une intrusion gabbroïque. Le levé sismique 3D de Matagami démontre que cette technique permet d'identifier les dépôts SMV profonds et les contacts lithologiques à l'échelle régionale. Le coût d'un levé 3D est comparable à celui de deux trous de forage d'une profondeur de 800 m par km².

En général, les roches du camp minier de Matagami sont réfléchives et les dépôts ne sont pas particulièrement riches en minéraux d'impédance acoustique élevée (i.e. pyrite et magnétite). L'intégration de la sismique réflexion 3D en exploration minérale sera facilitée par un environnement où la roche hôte sera peu réfléchive et de faible impédance acoustique et où les gisements sont associés à de grande quantité de pyrite

et de magnétite. Lorsque appliquée dans un environnement géologique favorable, la sismique 3D a le potentiel d'assister l'exploration minérale profonde et d'accroître les chances de faire des nouvelles découvertes tout en réduisant les coûts d'exploration.

ABSTRACT

The objective of this study is to evaluate the applicability of the 3D seismic reflection method, which is routinely applied in oil and gas exploration, to prospecting for deep volcanogenic massive sulphides (VMS). The Matagami mining camp of the Abitibi greenstone belt is well suited for this study because geological units have a moderate dip ($\sim 45^\circ$) and most geological contacts can be traced for tens of kilometres. Petrophysical studies performed in situ (boreholes) and on rock samples have demonstrated that rhyolite-gabbro contacts were likely to generate strong seismic reflections. The good reflectivity of lithological contacts in the Matagami mining camp allow seismic methods to map them to depths exceeding 3 km. Sample analyses from the Isle-Dieu orebody and borehole logging of holes that intersect the Bell Allard deposit have also shown that massive and semi-massive sulphides could be reflective. In particular, sulphides rich in high-impedance minerals (e.g. pyrite and magnetite) should generate anomalously strong reflections if their size is sufficient. In 1994, a 2D seismic profile acquired directly above Bell Allard identified a geophysical anomaly corresponding to the ore deposit. Since 2D seismic reflection profiles are inherently ambiguous as to the source of a given reflection, a vertical seismic profile (VSP) was deemed necessary to demonstrate the reflectivity of Bell Allard. The VSP section displays a strong compressional wave reflection and converted shear wave produced by the Bell Allard sulphides. A modelling study was undertaken, using existing borehole geometries, to evaluate the performance of VSP technology as a mineral exploration

tool. The modelled VSP section showed weak amplitude reflections for any shot location. Hence, the VSP method is not recommended for exploration in the Matagami mining camp.

In 1996, a 20 km² 3D seismic survey was collected above the 1 km deep Bell Allard ore deposit. The survey objectives were to identify the seismic response of a VMS ore deposit and to map the main lithological contacts. The Bell Allard VMS deposit appears as a 100 m wide zone of high seismic amplitudes. The deposit is underlain by a larger amplitude anomaly that we attribute to a gabbro sill, or possibly to the alteration zone of the deposit. The study shows that the depth of the main exploration target (the Key Tuffite) can be interpreted over a large portion of the seismic survey area, and that its southwest limit defines the location of a regional fault (the Daniel fault). The Matagami 3D seismic experiment indicates that seismic methods have the potential to image deep VMS deposits and map important lithological contacts at a regional scale for the equivalent cost of two 800 m deep boreholes per square kilometre.

In general, the volcanic and intrusive rocks of the Matagami mining camps are reflective and ore deposits are not particularly enriched in high-impedance minerals (e.g. pyrite and magnetite). In this mining camp, the strong reflectivity of the host rocks partly mask the orebody anomaly. Thus, 3D seismic reflection technology has limited usefulness in Matagami and will be more effective in a geological environment where the host rocks are seismically transparent and of low acoustic impedance and where the ore deposits are associated with large amounts of pyrite and magnetite. When applied in the appropriate geological context, a 3D seismic survey has the potential to assist deep mineral exploration and increase the chances of making cost-effective discoveries.

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CHAPITRE 1

INTRODUCTION

1.1 Problématique

C'est en 1963 que le camp minier de Matagami a été établi à la suite de la découverte du gisement de Mattagami Lake par méthodes géophysiques aéroportées (Paterson, 1966). Depuis cette découverte initiale, de nombreux gisements de moindre importance ont été découverts dans la région desquels du zinc et du cuivre ont été extrait de façon ininterrompue. Le camp minier de Matagami est l'un des principaux producteurs de zinc au Canada, métal pour lequel le Canada était le premier producteur mondial en 1997 (statistiques du Ministère des Ressources Naturelles du Canada). Les gisements riches en zinc de la région de Matagami sont du type sulfures massifs volcanogènes (SMV) archéens décrits par Franklin et al. (1981). Alors que seulement 22% de la production mondiale de zinc provient des SMV, au Canada c'est presque 50% (Singer 1995). Par conséquent, l'exploration pour les gisements SMV est non seulement importante pour l'économie canadienne, mais aussi pour l'approvisionnement mondial de zinc. En 1997, la production de zinc du camp minier de Matagami comptait pour 6.7% du total canadien, il est donc un important producteur. L'un des attraits des SMV pour les compagnies minières est qu'ils sont généralement polymétalliques et ainsi moins sensibles aux variations de prix d'un métal donné.

Néanmoins, les gisements SMV sont souvent de faible tonnage (la médiane est de 1.25 millions de tonne) : donc, pour être économique, la plupart doivent être situés à proximité de gisement plus gros (Riverin, 1999). Depuis la découverte initiale du gisement Mattagami Lake, l'exploration, pour identifier de nouveaux gisements, a progressé de la surface pour maintenant atteindre des profondeurs excédant 1000 m. Jusqu'à ce jour, l'industrie minière a surtout utilisé le forage au diamant de pair avec des levés géophysiques en forage (Boivin et Lambert, 1997) pour localiser les gisements SMV profonds puisque les autres méthodes géophysiques conventionnelles de surface (électromagnétiques, champs potentiels, électriques, etc.) n'ont que des profondeurs de pénétration ne dépassant pas 300 m. La petite taille des gisements SMV et les coûts élevés de forage à grande profondeur (83 \$/m, en 1996, selon les statistiques du Ministère des Ressources Naturelles du Canada) forcent les compagnies d'exploration à optimiser et à mieux cibler les forages pour réduire leur budget d'exploration. Par contre, les techniques d'explorations profondes conventionnelles ne semblent pas porter fruits. Aussi, dans la ceinture de roches vertes de l'Abitibi, seulement 4 mines dont le sommet est à plus de 500 m avaient été découvertes jusqu'à 1990 (Lulin, 1990) alors que la région comptait plus de 150 mines proches de la surface ou dont le sommet était à moins de 500 m de profondeur. Bien que ces statistiques décrivent un portrait sombre de l'exploration minérale en Abitibi, il faut considérer que l'exploitation d'un gisement requiert un tonnage et une teneur qui croissent avec la profondeur. Ainsi, les chances de trouver un gisement économique décroissent lorsque la profondeur augmente. Les techniques d'exploration profonde pour les gisements SMV dépendent fortement du modèle géologique pour établir les cibles de forage. Les levés électromagnétiques en forage utilisés de façon systématique permettent de détecter la présence de corps conducteurs à l'intérieur d'un rayon de 100 à 150 m autour du trou de forage (Lavalière et al., 1994; Boivin et Lambert, 1997). Par contre cette tech-

nique d'exploration ne permet pas de cibler les trous de forage profond au-delà des limites du modèle géologique. L'exploration de surface bénéficie de levés aéroportés et de surface peu coûteux (e.g. électromagnétique et magnétique) pour localiser les dépôts conducteurs ou magnétiques. Ces levés sont souvent inadéquats pour assister les programmes d'exploration profonde dans le camp minier de Matagami à cause de leur faible profondeur de pénétration et leur basse résolution à grande profondeur. Les compagnies d'exploration minérale ont donc besoin de méthodes géophysiques pouvant jouer un rôle similaire aux levés électromagnétiques et magnétiques mais avec une profondeur de pénétration supérieure à 500 m. De telles techniques seraient surtout utiles dans les camps miniers matures puisqu'elles permettraient de mieux cibler les forages profonds et d'identifier rapidement de nouveaux gisements.

1.2 Objectifs et méthodologie

L'objectif principal de ce projet de recherche est de développer une méthodologie permettant d'identifier la présence de dépôts de type SMV à grande profondeur. La découverte de nouveaux gisements dans les camps miniers matures de l'Abitibi et ailleurs au Canada est un enjeu politique lorsque certaines villes minières sont menacées de fermeture par manque de nouvelles ressources minérales. Pourtant, l'identification de dépôts économiques dans les camps miniers existant est souvent plus avantageuse que la découverte de ressources minérales dans des régions peu accessibles et peu développées. En effet, en mettant en production des gisements dans les camps miniers existant, il n'y a pas de transfert de population et l'utilisation des infrastructures existantes est maximisée. À l'ère où les gouvernements encouragent le développement durable et supportent de moins en moins la création de "villes champignons", il est clair que l'exploration des camps miniers existants est politiquement, économiquement et socialement viable. D'autre part, les infrastructures minières étant

souvent payées par les mines précédentes et la main d'œuvre qualifiée étant déjà sur place, il est souvent plus rentable pour les compagnies d'exploiter de plus petits gisements dans un camp minier établi que de mettre en production un gisement plus gros dans une région peu accessible. Mais l'exploration profonde présente tout un défi puisque les méthodes permettant de cibler les trous de forage à des profondeurs supérieures à 500 m sont pratiquement inexistantes. Il y a donc toujours un élément de chance dans la découverte d'un gisement profond. En plus, les compagnies minières sont réticentes à quitter une région sans savoir si un gisement de classe mondiale s'y trouve. Mais puisque le forage systématique à grande profondeur coûte cher et prend beaucoup de temps, il s'avère nécessaire de développer une technique permettant d'explorer de façon systématique le sous-sol des camps miniers.

Le programme pan-canadien Lithoprobe, initié au début des années 80, a fait connaître la sismique réflexion 2D aux compagnies minières de l'Abitibi. En 1990, un profil sismique haute-résolution est réalisé dans le camp minier de Matagami et produit la première image sismique de sa stratigraphie profonde. Cette première étude, présentée dans l'article 1 (voir Chapitre 2), a permis d'imager des contacts lithologiques et des structures importantes pour l'exploration à Matagami. Les mesures pétrophysiques en forage ont démontré que des unités de rhyolite, intercalées avec des gabbros et des basaltes, étaient responsables des fortes réflexions observées sur le profil sismique. Ces unités de rhyolite (rhyolite Supérieure et rhyolite de Dumagami) sont situées au-dessus de la Tuffite Clé, horizon auquel la plupart des dépôts du camp minier sont associés. Les unités rhyolitiques présentes dans le Groupe de Wabasee Inférieur font de ce dernier un marqueur sismique permettant d'estimer la position et la profondeur de la Tuffite Clé. Par contre, les données sismiques n'ont permis l'identification d'aucun dépôt SMV bien que deux dépôts connus se trouvaient à proximité du profil sismique.

Le deuxième article (voir Chapitre 3) est une synthèse de tous les profils sismiques haute-résolution acquis dans le cadre du transect Abitibi-Grenville du projet Lithoprobe (Selbaie, Matagami, Sudbury, et Noranda). La synthèse montre que l'intégration des données sismiques, pétrophysiques et de forages profonds permet de définir la cause des réflexions sismiques. En particulier, les études pétrophysiques sont la clé de l'interprétation des profils sismiques et ont permis de définir des horizons sismiques marqueurs (e.g. le "footwall complex" à Sudbury et le Groupe de Wabassee Inférieur à Matagami). La découverte du gisement Bell Allard en 1994 à une profondeur de 950 m, procurait la cible idéale pour évaluer différentes méthodes sismiques en exploration minière. Bien que les profils sismiques effectués au-dessus de dépôts connus présentaient des anomalies distinctives, l'ambiguïté quant à la nature des réflexions (galeries de mines ou sulfures massifs) et à leur position (problème de "side-swipe") nécessitait l'utilisation du profilage sismique vertical (PSV) pour confirmer la réflectivité des gisements de type SMV.

Le troisième article (voir Chapitre 4) présente les résultats de deux PSV réalisés à proximité de Bell Allard. Cette étude démontre que le gisement Bell Allard produit une forte réflexion sismique. Des simulations numériques pour optimiser l'utilisation des PSV en exploration n'ont pas été concluantes : les amplitudes maximales des réflexions des sections PSV synthétiques dans des trous de forage situés à des distances de 200 m et de 700 m de Bell Allard étaient faibles. Depuis le début des années 80, la sismique réflexion 3D a eu un impact monumental sur l'exploration pétrolière (Nestvold, 1992). Les coûts d'acquisition supérieurs des levés 3D, comparativement aux profils sismiques 2D traditionnels, sont amplement compensés par l'amélioration du taux de réussite des trous de forage (Greenlee, 1994). Un levé sismique réflexion 3D apparaissait donc comme la solution idéale pour identifier les SMV profonds. Le levé a été réalisé en avril 1996 pour couvrir une région de 20 km² incluant le dépôt

de Bell Allard.

Le quatrième et dernier article (voir Chapitre 5) présente les résultats du levé 3D qui a imagé le gisement Bell Allard et défini la limite sud-ouest du camp minier. Cette étude montre que la sismique est un outil efficace pour explorer la partie profonde des camps miniers. L'industrie minière bénéficie directement des développements technologiques de l'industrie pétrolière en matière de sismique réflexion 2D, 3D et PSV, puisque que les méthodes sont applicables sans modification à l'acquisition, au traitement et à l'interprétation des données.

CHAPITRE 2

SEISMIC REFLECTION AND BOREHOLE GEOPHYSICAL INVESTIGATIONS IN THE MATAGAMI MINING CAMP

2.3 Introduction

Cet article, intitulé "Seismic reflection and borehole geophysical investigations in the Matagami mining camp", fut publié en juin 1998 dans la Revue canadienne des sciences de la Terre. Le résultat le plus important de cette étude est l'identification d'unités de rhyolite (Supérieure et de Dumagami) situées au-dessus de la Tuffite Clé, horizon auquel la plupart des dépôts du camp minier sont associés. Les unités rhyolitiques du Groupe de Wabasee constituent un marqueur sismique permettant de localiser la position et la profondeur de la Tuffite Clé. Par contre, les données sismiques n'ont pas permis l'identification de dépôt SMV bien que deux dépôts connus se trouvaient à proximité du profil.

C'est dans le cadre du projet Lithoprobe, que ce levé sismique réflexion haute-fréquence a été réalisé, dans un secteur du camp minier de Matagami où la géologie est bien connue, afin de vérifier l'efficacité de la méthode à cartographier les contacts lithologiques à grandes profondeurs. Les données ont été retraitées afin de rehausser les

réflexions peu profondes. Les étapes du traitement permettant d'imager les structures géologiques superficielles sont : les corrections statiques de réfraction, les corrections pour le pendage latéral, ainsi que l'élimination des ondes réfractées. Des diagraphies de densité et de vitesse sismique dans deux sondages localisés à proximité du profil ont permis de calibrer la section sismique. L'analyse des propriétés physiques des roches suggère que les fortes réflexions proviennent des contacts entre les rhyolites et les gabbros. La présence d'horizons rhyolitiques dans le Groupe de Wabasse Inférieur, qui est principalement composé de basaltes et de gabbros, fait de cette séquence un marqueur sismique. Or, l'horizon, au niveau duquel se trouve la plupart des gisements, est situé à la base de cette séquence réflective. Dans le camp minier de Matagami, la sismique réflexion s'avère un outil efficace pour cartographier la stratigraphie et les structures géologiques profondes.

2.4 Article 1

Seismic reflection and borehole geophysical investigations in the Matagami mining camp

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Geological Survey of Canada contribution 1997158

Lithoprobe Contribution 988.

2.4.1 Abstract

A high-frequency vibroseis seismic survey was conducted by Lithoprobe across a well known section of the Matagami mining camp to assess the usefulness of seismic methods in lithological mapping. The data have been reprocessed to enhance shallow reflections. Critical processing steps for the preservation of the shallow features include refraction static corrections, cross-dip corrections, and first break mutes. The seismic data were calibrated using geophysical logs from two boreholes adjacent to the profile. Physical rock property measurements suggest that strong reflectivity within the volcanic sequence occurs at rhyolite/gabbro contacts. The Lower Wabassee Group, a sequence of gabbros and basalts with interlayered rhyolite horizons, has been identified as a seismic marker. This reflective package overlays the horizon where most sulphide deposits are known to be located. In the Matagami mining camp, seismic reflection methods can be used to map the deep volcanic stratigraphy and structures.

2.4.2 Résumé

Dans le cadre du projet Lithoprobe, un levé sismique réflexion haute-fréquence a été effectué, dans un secteur du camp minier de Matagami où la géologie est bien connue, afin de vérifier l'efficacité de la méthode à cartographier les contacts lithologiques à grandes profondeurs. Les données ont été retraitées afin de rehausser les réflexions peu profondes. Les étapes de traitement de données permettant d'imager les structures géologiques superficielles sont les corrections statiques de réfraction, les corrections pour le pendage latéral, ainsi que l'élimination des ondes réfractées. Des diagaphies de densité et de vitesse sismique dans deux sondages localisés à proximité du profil ont permis de calibrer la section sismique. L'analyse des propriétés physiques des roches suggère que les fortes réflexions proviennent des contacts entre les rhyolites et les gabbros. La présence d'horizons rhyolitiques dans le Groupe de

Wabassee Inférieur, qui est principalement composé de basaltes et de gabbros, fait de cette séquence un marqueur sismique. Or, l'horizon, au niveau duquel se trouve la plupart des gisements, est situé à la base de cette séquence réflective. Dans le camp minier de Matagami, la sismique réflexion s'avère un outil efficace pour cartographier la stratigraphie et les structures géologiques profondes.

2.4.3 Introduction

As part of the Lithoprobe Abitibi-Grenville project, 8.72 km of high-frequency seismic reflection data were acquired across the Matagami mining camp. Most orebodies in the camp are located along an extensive marker horizon called the Key Tuffite. Exploration of the Key Tuffite by systematic drilling becomes quite expensive as its depth increases, thus the use of seismic reflection.

The Key Tuffite is too thin ($< 6\text{m}$) to be resolved seismically with the parameters of this survey, but is located at the contact between the mafic Wabasse Group and the felsic Watson Lake Group. Previous studies in the Canadian Shield (e.g., Adam et al. 1991; Milkereit et al. 1992; Verpaelst et al. 1995) and other crystalline environments (Dahle et al. 1985; Juhlin 1990; Juhlin et al. 1991) demonstrated that strong reflections originate from lithological contacts between felsic and mafic rock units. Seismic methods allow indirect mapping of the Key Tuffite by imaging the base of the Wabasse Group. In the test area, the mineralized contact dips to the southwest at 45° , making it a suitable target for surface seismic profiling. Calibration of the seismic data was achieved by acquiring part of the data in an area of good stratigraphic control from deep boreholes. Results from geophysical logging of two deep boreholes close to the seismic profile were also used to relate the seismic data to known geology and to establish the seismic stratigraphy of the Matagami volcanic complex.

2.4.4 Geological setting

The Matagami mining camp is located in the northern part of the Abitibi Sub-province, one of the largest Archean greenstone belts in the world. The volcanic belt is well preserved, but it has suffered multiple deformation phases that have produced a mosaic of relatively small fault-bounded terranes (Ludden et al. 1986; Daigneault and Archambault 1990). The Matagami volcanic complex is part of one of these terranes.

The study area is covered by overburden of glacial origin consisting of clay, sand, gravel, and till of variable thickness from 0 to more than 70 m (MacLean and Davidson 1977). Swamps and muskegs cover much of the area and most geological information has been gathered through stratigraphic drilling and geophysical surveys (Piché et al. 1993).

Rocks of the Matagami volcanic sequence (Fig. 2.1) were formed by two major phases of volcanism: the initial phase was dominated by the extrusion of tholeiitic rhyolite and rhyodacite lavas (the Watson Lake Group), and the second phase was characterized primarily by calc-alkaline basaltic to andesitic volcanism (the Wabasee Group) (MacGeehan and MacLean 1980; Beaudry and Gaucher 1986). The lower 500 m of the Wabasee Group (referred as the Lower Wabasee Group) includes several exhalites and tuffs and a thick (> 200 m) layer of spherulitic rhyolite called the Dumagami unit (Piché et al. 1993). The stratigraphy above the Lower Wabasee Group is more homogeneous and forms the Upper Wabasee Group. MacLean (1984) estimated the Watson Lake Group to be about 1 km thick with increases up to 2 km due to mafic sills, and the Wabasee Group to be at least 5 km thick. At the contact between the Watson Lake and Wabasee groups, a continuous horizon of cherty exhalite, called the Key Tuffite, is observed throughout the camp. This thin exhalative horizon (0.6 - 6 m) was deposited during a period of intense hydrothermal activity and

hosts most of the massive sulphide deposits found to date in the Matagami mining camp (Piché et al. 1993). The volcanic units were intruded by the Bell River Complex, a syn-volcanic gabbro-anorthositic layered intrusion believed to be the source of heat that initiated the hydrothermal circulation that formed the orebodies (MacLean 1984). U-Pb dating (Mortensen 1993) also suggests that the Watson Lake Group and the Bell River Complex may be co-magmatic, since they have overlapping ages ranging between 2726.3 and 2722.4 Ma. After the extrusion of the Wabassee Group, the whole sequence was folded to form the northwest-southeast trending Galinée anticline (Fig. 2.1). The north flank of the anticline is nearly vertical and has been disrupted by numerous faults associated with the Garon Lake high-strain zone (Piché et al. 1993). Comparatively, the southern flank is relatively undeformed and dips more gently ($\sim 45^\circ$) to the southwest (Piché et al. 1993; Lavallière et al. 1994).

A major north-northwest trending reverse fault, the Daniel fault (Fig. 2.1), cross-cuts the Galinée anticline (Piché et al. 1990). The vertical displacement associated with this near vertical fault plane is about 1500 m at the Galinée fold axis, but farther south, where it intersects seismic line 29-3, the offset has not been verified by drilling.

2.4.4.1 Seismic data acquisition

Line 29-3 was acquired along an east-west mine road up to highway 109 (stations 200 and 208) and along a logging road (Fig 2.1). Since Barnes et al. (1995) have presented an exhaustive appraisal of the Abitibi-Grenville seismic reflection acquisition parameters (Table 2.1), only problems and conditions specific to the acquisition of seismic profile 29-3 are outlined here. Ambient noise was generally low, but the signal was locally contaminated by electrical noise near a high-voltage substation (near stations 197-199), broadband noise due to ongoing diamond drilling (near station 300) and low-frequency highway noise. As for most Lithoprobe seismic surveys

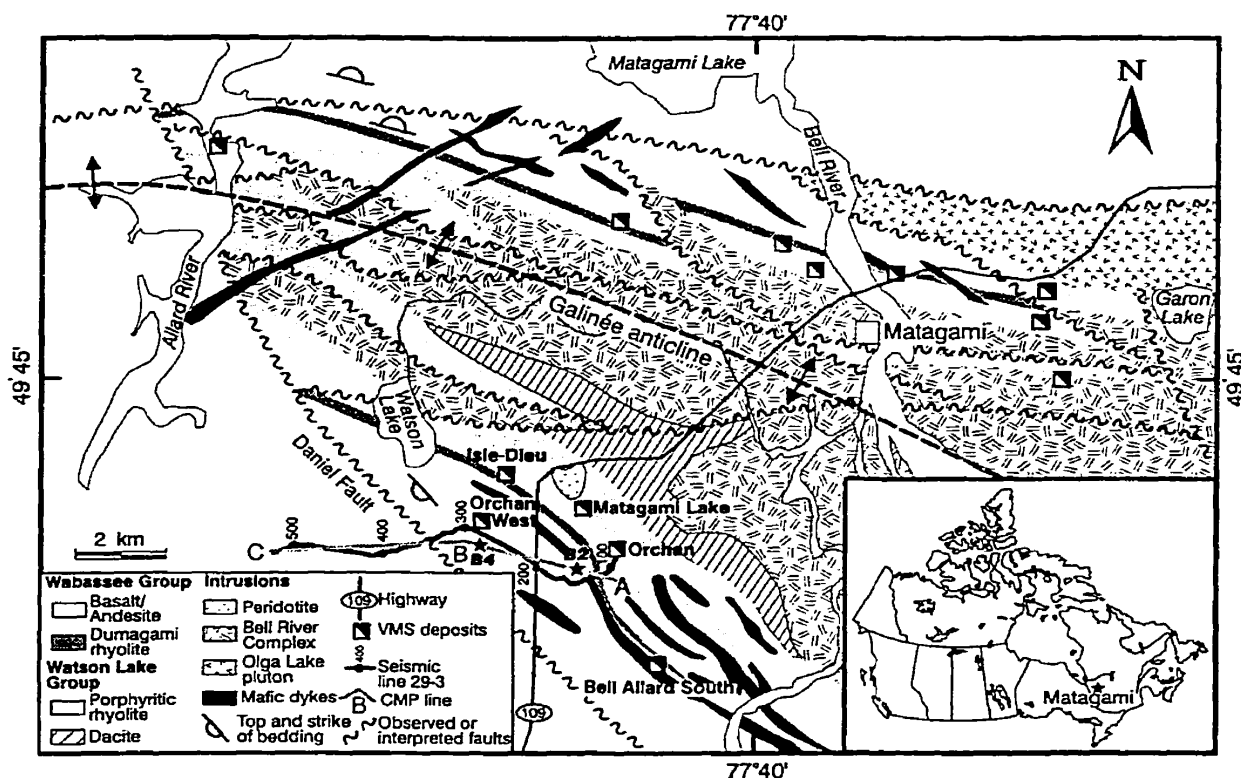


Figure 2.1: Geological map of the Matagami mining camp showing main lithological units, location of seismic profile 29-3 and location of boreholes (B2, B4) used to constrain the interpretation. The CMP line used for processing is also indicated (A, B, and C) (modified from Piché et al., 1993). VMS, volcanogenic massive sulphides

in the Abitibi belt, strong shear wave refractions were recorded and they obscure a significant portion of the shallow reflections (Barnes et al. 1995).

Because of the high nominal fold (120) and only localized occurrence of bad traces, most noise contamination did not cause major data processing problems and did not require severe trace editing. However, the challenging task was to preserve shallow dipping reflections necessary to image the stratigraphy of this Archean volcanic complex.

Table 2.1: Data acquisition parameters

Source Information	
Energy source	Two MERTZ Model-18 Vibrators
Source interval	20 m
Sweep length	12 s
Sweep spectrum	30 - 140 Hz linear
Sweep repetition	4
Receiver Information	
Geophone type	30 Hz MARK PRODUCTS L-25
Geophone interval	20 m
Geophone layout	9 over 20 m
Coverage	120 fold
Spread	120/120 split, no gap
Acquisition System	
Instrumentation	240 Channel SERCEL SN368
Gain type	Floating point
Field filter	178 Hz High-cut
Record length	4 s
Sample rate	2 ms

2.4.4.2 Data processing

The high-frequency seismic data collected in the Matagami mining camp are affected by severe overburden thickness variations and a crooked seismic profile intersecting geological contacts at angle. An initial dip-moveout (DMO) processing sequence was presented by Milkereit et al. (1992). These initial results showed a good overall seismic image of the south flank of the Galinée anticline, but lacked continuous reflections in the upper 0.5 s. The seismic signatures of the Wabassee and Watson Lake groups were clearly established and they allowed the indirect mapping of the Key Tuffite at the base of the reflective Wabassee Group. Here we present key processing steps (Table 2.2) which have enhanced the shallow reflectivity. The reprocessed unmigrated stacked section of seismic line 29-3 is shown in Fig. 2.2. Reflections and diffractions (respectively marked as R and D on Fig. 2.2) are imaged

Table 2.2: Processing Sequence

Crooked line geometry	
Refraction statics*	
- First break picks	Manual on every shot
- Datum	300 m Above Sea Level
Stacking velocity analysis	Constant-velocity stacks
Cross-dip analysis	In steps of 2.5°
First break mutes*	30 ms below the first breaks
Cross-dip corrections*	
Spectral balancing	30-140 Hz
NMO corrections	55% stretch allowed
Surface consistent residual	window: 0.1- 1.2 s
static corrections	Maximum shift: 15 ms
DMO corrections	
Stacking velocity analysis	Constant-velocity stacks
Scale	0.0 - 2.0 s, 150 ms
	(automatic gain control)
Stack	
Migration	FK (6000 m/s)
Coherency enhancement	
*Critical steps for the enhancement	
*of shallow reflections	

from 0.15 s (~ 500 m), facilitating correlation with lithologies intersected by nearby boreholes.

Crooked line geometry

Conventional crooked line geometry binning using a smooth slalom line is often characterized by lower fold and uneven offset range where the seismic line changes direction resulting in poor seismic images (Wu 1996). To avoid this problem, the straight-line binning approach proposed by Wu (1996) was adopted. Seismic line 29-3 was processed as two separate seismic profiles (marked as segment AB and BC on Fig. 2.1). This simple common midpoint (CMP) line geometry was chosen to produce an undistorted seismic section that can be properly migrated by facilitating cross-dip

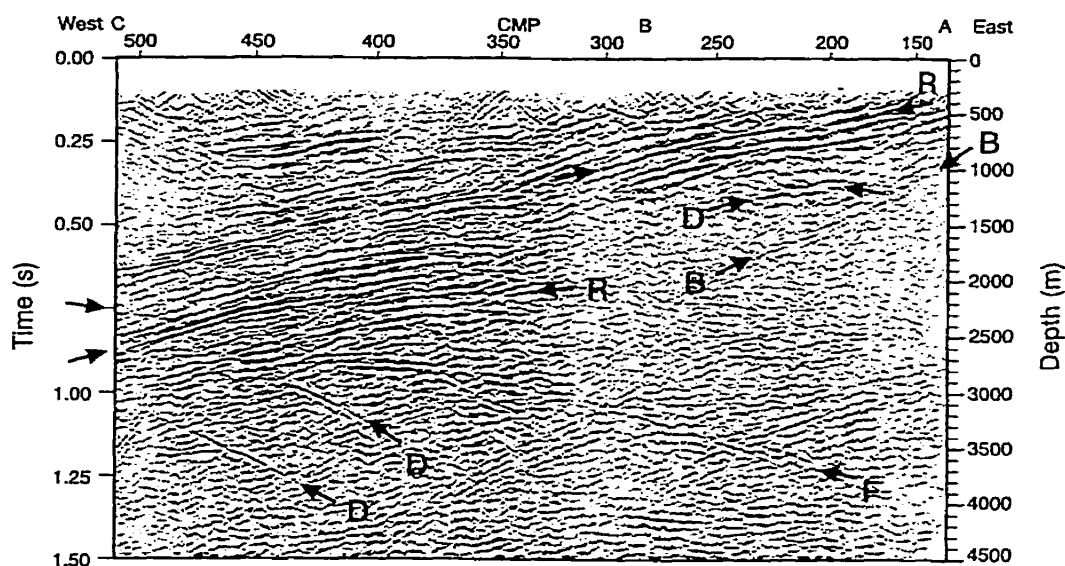


Figure 2.2: Unmigrated DMO stack of line 29-3. The seismic data has been reprocessed using the sequence presented in Table 2.2, a better image of shallow steeply dipping reflections is attributed to accurate static corrections, to cross-dip corrections, careful muting of the first breaks and allowing a NMO stretch of 55%. B, possible contact of the Bell River Complex with the Watson Lake Group; D, diffraction; F, possible east-dipping thrust fault; R, reflection.

analysis and maintaining an even fold distribution and offset range. The crooked line geometry definition was an important processing step since the structurally complex zone (Daniel fault) is directly beneath a major bend of the seismic profile. The CMP line location was also constrained by the location of the deep boreholes later used for the interpretation.

Refraction static corrections

The importance of accurate refraction static corrections in a crystalline environment is generally recognized (Milkereit et al. 1992; Wu et al. 1992; Juhlin 1995). For instance, static shifts of as much as 51 ms were required to compensate for thick low velocity (<1500 m/s) overburden. The importance of refraction static corrections for this type of data is due to several factors: *i*) high velocity of the basement rocks

(> 6000 m/s) relative to the overburden results in large static shifts, *ii*) preservation of the high-frequencies contained in the data requires accurate static correction, and *iii*) low signal-to-noise ratio of the data and the magnitude of the static shifts prevent the successful static correction estimation using residual static algorithms. Because of the highly variable overburden conditions in the Matagami region, first arrivals were picked on all shot gathers, and three different static correction algorithms were tested (Farrell and Euwema 1984; Hampson and Russell 1984; Hatherly et al. 1994). The generalized linear inversion method of first arrivals (Hampson and Russell 1984) resulted in the best refraction static estimates.

Velocity analysis and normal moveout stretch mute

Analysis of constant-velocity stacks for the complete profile has revealed a simple velocity field. Stacking velocities increase from 6.2 km/s at the surface to 6.5 km/s at 1.2 s with minor lateral velocity variations. Miller (1992) noted the choice of normal moveout (NMO) stretch factor as a possible pitfall in shallow seismics: allowing too much stretch may reduce the dominant frequency and bandwidth of the signal. On the other hand, a severe NMO stretch mute may destroy shallow reflections and this is most critical for dipping reflections because most of the reflected energy is located down dip and in the far offset traces. The contribution from the far offset traces for imaging dipping shallow reflectors has also been recognized by Juhlin (1995). We found that muting data stretched by 55% or more was a good compromise for preserving shallow information while maintaining the bandwidth of the data. Because shallow reflections are affected by the presence of first break energy, our mute functions were established at 30 ms below the first break (Wu et al. 1995). Surface consistent residual static corrections applied after NMO corrections (Ronen and Claerbout 1985) produced only a minor improvement of the seismic image.

Cross-dip and dip-moveout corrections

The crookedness of the seismic line produces an off-line scattering of the midpoints where the line changes orientation. Because of the steep dips of the lithological contacts, the scattered midpoints grouped in a CMP gather show reflections from the same lithological contact, but from various depths. Consequently, the events recorded in an area of scattered midpoints cannot stack properly. Solutions to this problem were presented by Larner et al. (1979), West and Wang (1992) and Kim et al. (1992). Our cross-dip analysis, using constant cross-dip corrected (2.5° intervals) stacked sections, showed minor cross-dip variations with time. The optimum cross-dip correction was estimated at 15° on the eastern segment of the CMP line and at 10° to the west.

The production of high-quality seismic images of the dipping volcanic sequence requires the use of different stacking velocity functions depending on the dip of the reflector. Thus, dip-moveout corrections *must* be applied to allow reflectors of various dips to stack coherently using the same velocity function. The improvement from this correction was particularly obvious in the vicinity of the Daniel fault (CMP 320 - CMP 360). Figure 2.3 shows the unmigrated stacked section of that key portion of line 29-3 after four different processing sequences: (i) the initial processing sequence without DMO correction (Fig. 2.3a), (ii) same as (i) but with DMO correction (Fig. 2.3b) (Milkereit et al. 1992), (iii) the reprocessed section including cross-dip corrections (Fig. 2.3c), and (iv) same as (iii) but with DMO corrections (Fig. 2.3d). Clearly, the initial processing sequence failed to image the steep dip of the volcanic sequence in the vicinity of Daniel fault. DMO corrections, without cross-dip corrections, improved the seismic image, but the apparent dip was overestimated, most likely because of the scattering of the midpoints where the line was not straight (B on Fig. 2.1).

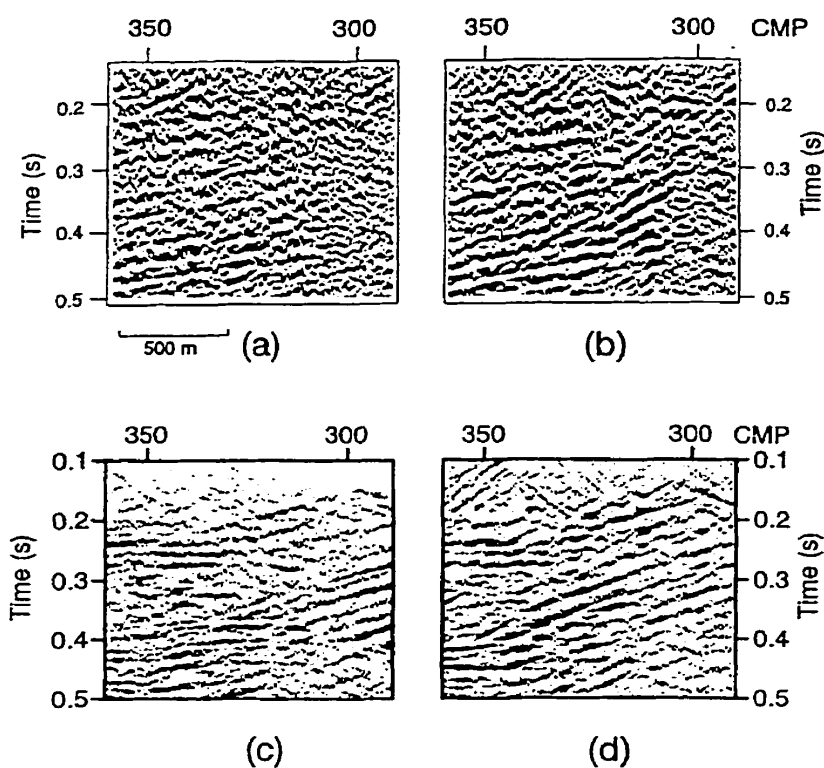


Figure 2.3: Comparison of different processing sequences on a key portion of line 29-3. (a) After initial processing without DMO corrections. (b) Same as (a) but with DMO corrections. (c) Reprocessed section with cross-dip corrections. (d) Same as (c) but with DMO corrections.

2.4.4.3 Borehole logging

Two boreholes, marked as B2 and B4 in Fig. 2.1, were logged to study the in situ physical properties of the Wabasee and Watson Lake groups. Hole B2 is 758 m deep and intersects the Key Tuffite at a depth of 685 m. The second hole, located near the Daniel fault, is 1442 m deep and reaches the Key Tuffite at 1291 m. Densities measured at 10 cm intervals in hole B2 provide information about the Key Tuffite, and data collected at a 1 m spacing in hole B4 give information about more than 1200 m of Wabasee Group lithologies. In addition, compressional wave velocities were extracted from full waveform sonic logging conducted at a 10 cm interval in both drill holes. Physical rock property measurements are essential for understanding the

reflectivity of lithological units, as the amplitude of seismic reflections is a function of the acoustic impedance (the product of density and compressional wave velocity).

Density logging

The upper 850 m of hole B4 (Fig. 2.4) intersects a homogeneous sequence of basalts and gabbros characterized by a nearly constant density of $\sim 2.95 \text{ g/cm}^3$ (except for limited zones of fractures, faults, or felsic dykes). We attribute the increased abundance of fractures and faults in hole B4 to the proximity of the Daniel fault. Below 850 m, densities decrease to about 2.8 g/cm^3 in the presence of rhyolite units.

Densities measured in hole B2 (Fig. 2.4) follow the same trend as those from hole B4. The upper 200 m show high densities similar to those of the upper 850 m of hole B4, whereas the 400 m interval above the Key Tuffite shows reduced density values ($\sim 2.75 \text{ g/cm}^3$). The density measurements also show that gabbros intersected by hole B2 and B4 form two distinct groups: one group has densities comparable to those of basalts ($\sim 2.85 \text{ g/cm}^3$), whereas the second has densities around 3.0 g/cm^3 . The two types of gabbros can easily be distinguished on the geological logs, the dense gabbro being more magnetic.

Several horizons of exhalite, tuff, and rhyolite interlayered with gabbro and basalt are found in a 400 to 600 m thick package at the base of the Wabassee Group. This package of variable density differs from the overlying sequence of basalts and gabbros of nearly constant density (Upper Wabassee Group), and is referred to as the Lower Wabassee Group.

Full waveform sonic logging

To avoid skipping cycle when picking first arrival energy for estimating compressional (P) and shear (S) wave velocities, we used seismic reflection processing software to scale and filter the full waveform sonic data and to pick the first breaks

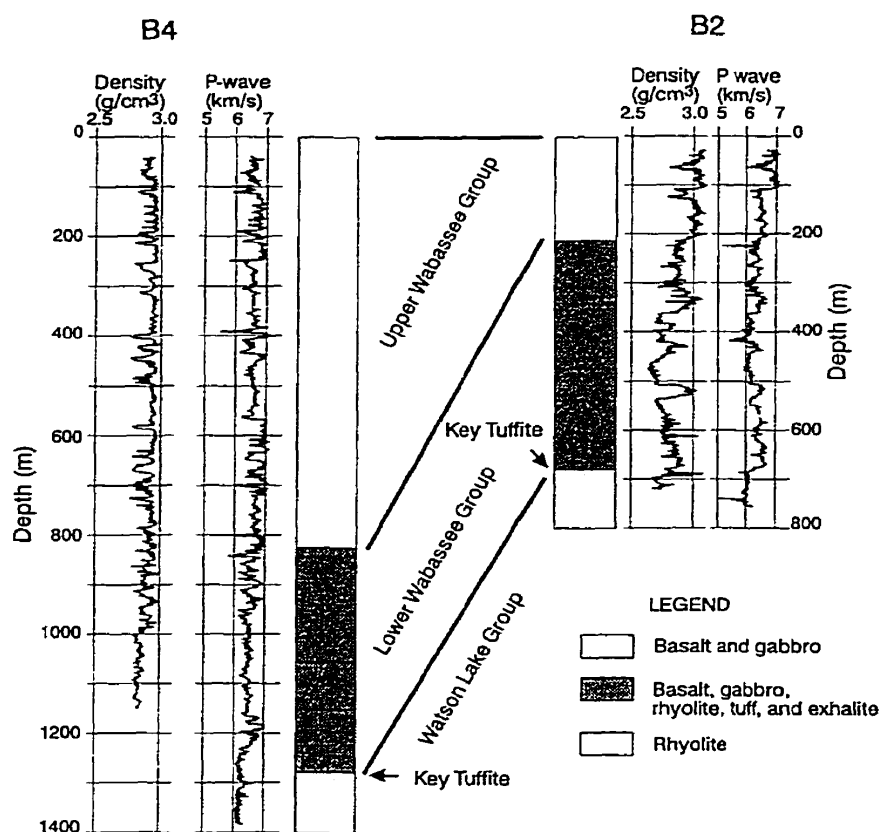


Figure 2.4: Lithologies, densities, and P-wave velocities for boreholes B4 and B2. Significant density and P-wave velocity variations are associated with the lower Wabasse Group.

on the far and near offsets. Interval velocities were then calculated from the ratio of the receiver spacing (0.3048 m) and the travel time difference between the near and far receivers. A portion of the near receiver waveform data collected in hole B2 is shown in Fig. 2.5. Note the clarity of the P- and S-wave arrivals. The good correlation between density and P-wave velocity for different lithological units is also obvious, as are the earlier P-wave arrivals in gabbro as compared to the rhyolites. On the other hand, S-wave velocities are higher in the quartz-rich rhyolites, translating into low Poisson's ratios for that lithology. Reduced Poisson's ratios are expected in felsic units (Fountain and Christensen 1989).

P-wave velocities measured in holes B2 and B4 are shown in Fig. 2.4. Velocities in

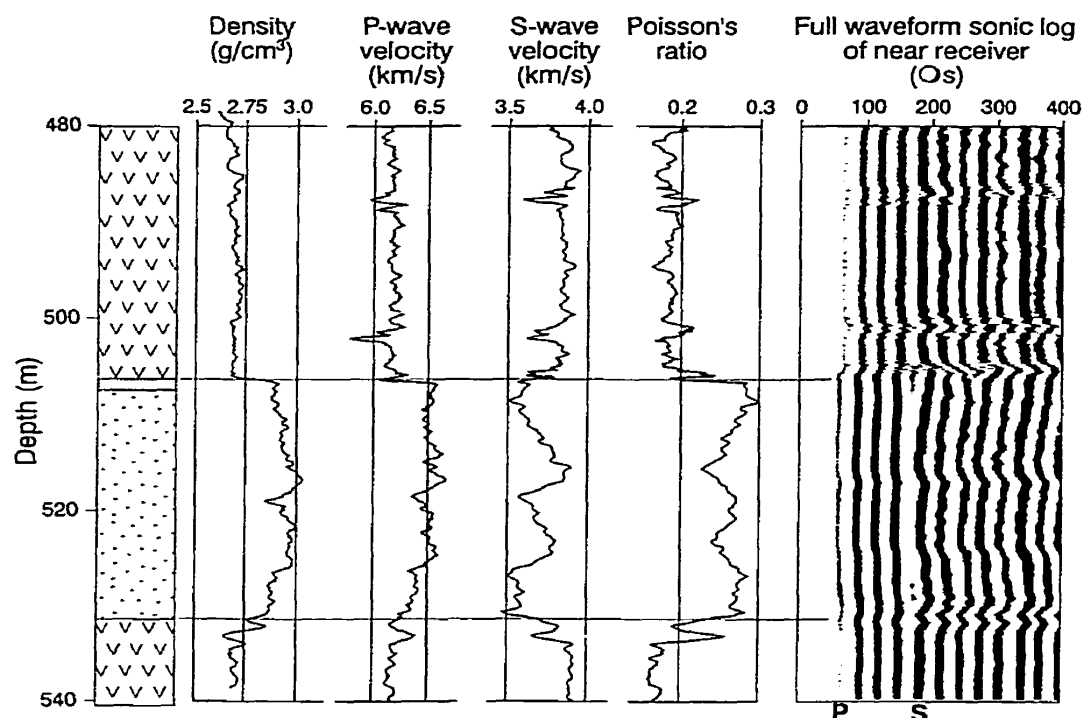


Figure 2.5: Results from full waveform sonic logging (near receiver) in a section of hole B2. High P-wave velocities and densities are associated with a gabbro unit. S-wave velocities are reduced in the gabbro, resulting in high values of the Poisson's ratio.

the 5.75 to 7.0 km/s range were found in most lithologies, and velocities as low as 4.25 km/s are attributed to faults and fractured zones. The fastest P-wave velocity (~ 7 km/s) was measured in a dense gabbro unit. Therefore, gabbros are expected to have the highest acoustic impedances. Rhyolites, tuffs, and exhalites are characterized by reduced acoustic impedances because they have a relatively low average P-wave velocity (~ 6.0 km/s) and the lowest densities (~ 2.7 g/cm³). Basalts are characterized by intermediate P-wave velocities (~ 6.3 km/s) and densities (~ 2.85 g/cm³), hence their acoustic impedances will fall between those of rhyolites and of gabbros.

This study suggests that, in the Matagami mining camp, the strongest reflections should occur at contacts between rhyolites and gabbros. The density and P-wave velocity variations associated to the lower Wabasse Group are also likely to produce

a package of good reflections and could possibly be used as a marker sequence for future seismic studies in the area.

Synthetic seismograms

The relation between the seismic data, the geological logs, and the physical rock properties measured in holes B2 and B4 was established by using synthetic seismograms (Fig. 2.6). The seismograms were derived by convolving the primary reflectivity function with a Ricker wavelet of 40 Hz central frequency. Reflections observed on the synthetic seismograms confirm that lithologic contacts are the main cause of reflections and that contacts between gabbros and rhyolites within the Lower Wabasse Group can generate strong reflections. One reflection, continuous over more than 3.5 km, matches the response on both seismograms and seems to originate from the top of a rhyolite unit, the Dumagami Rhyolite. This unit is located above the Key Tuffite and may constitute an important marker for further seismic surveys and for estimating the stratigraphic level in a faulted terrane. The synthetic seismogram from hole B2 confirms the lack of strong reflectivity associated with the Key Tuffite. Other reflections in the upper 125 ms of the synthetic seismogram can be attributed to open fractures and lithologic contacts which are too shallow to be imaged on the seismic section.

2.4.5 Interpretation

In an initial interpretation of this seismic profile (Milkereit et al. 1992), the strong reflectivity of the Lower Wabasse Group was recognized, but the lack of continuous reflections was attributed to multiple faulting in the vicinity of the Daniel fault zone. The Lower Wabasse Group was correlated west of the Daniel fault, suggesting a vertical displacement of about 500 m (Milkereit et al. 1992). Thus, the Daniel fault

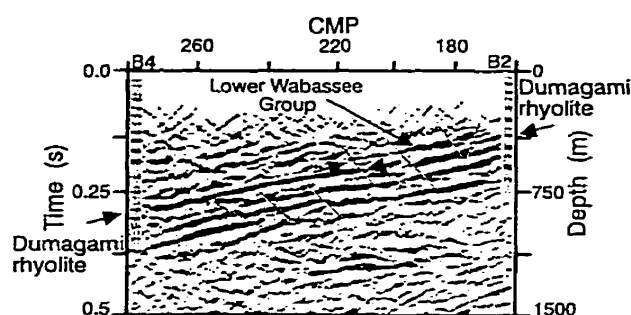


Figure 2.6: Relation between synthetic seismograms and a portion of the migrated section of line 29-3. Strong reflectivity is associated with the Lower Wabasse Group. A continuous reflection correlates with the top of a rhyolite unit (the Dumagami rhyolite).

is likely a reverse fault that downfaulted the Key Tuffite to a depth exceeding 1700 m on the west. Our final interpretation is constrained by the extensive amount of available geological information, particularly on the eastern section of the line (Fig. 2.1). The stratigraphy of the south flank of the Galinée anticline is well established (Beaudry and Gaucher 1986; Piché et al. 1993) and the third dimension of the Orchan mine property, at the eastern end of the seismic profile, is known from numerous boreholes. At the time of the seismic survey, ongoing exploration diamond drilling on the Orchan West property (Fig. 2.1) had extended the geological model down to 1.4 km. However, west of the Daniel fault there are no deep boreholes close enough to the seismic line to constrain our interpretation.

Stratigraphy

The main geological units are characterized by different seismic signatures: the Watson Lake Group is quasi non-reflective, the Upper Wabasse Group is locally reflective, and the Lower Wabasse Group is highly reflective and constitutes a good marker package (Fig. 2.7). The Bell River Complex, which outcrops 2 km to the east of the profile, is known to underlie the volcanic sequence. The edges of the Bell River Complex are composed of diorites and tonalites (Piché et al. 1990), therefore

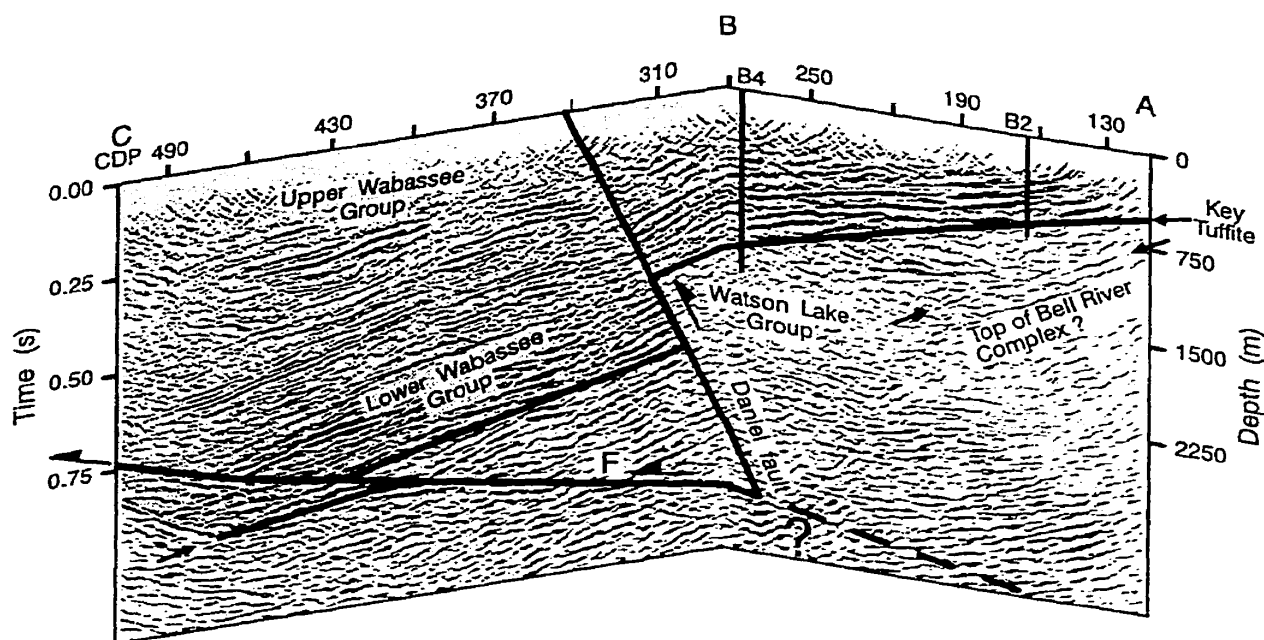


Figure 2.7: Migrated fence diagram of line 29-3. The main geological units and faults are indicated. The Key Tuffite is located at the base of the reflective Lower Wabasse Group. Note that the approximate depth scale has been calculated using a 6 km/s average crustal velocity.

its contact with the Watson Lake Group would be a poor reflector. The intrusive contact may correspond to a faint west-dipping reflection observed at ~ 2.3 km at the eastern end of the profile, suggesting a thickness of 1.5 km for the Watson Lake Group.

The main exploration target (the Key Tuffite) is too thin to be resolved with the acquisition parameters used in this survey, but due to its location at the contact between the rhyolites of the Watson Lake Group and the basalt, gabbro, rhyolite, exhalite and tuff units of the Lower Wabasse Group, reflections can be expected from this stratigraphic level. The Key Tuffite is not associated with an outstanding reflection and we attribute its lack of continuity to lithological variations within the Lower Wabasse Group. For instance, in hole B4, the Key Tuffite is overlain by a thick rhyolite, but in hole B2 it is in contact with a sequence of gabbros.

The continuous reflection near the top of the Lower Wabassee Group may correspond to the Dumagami rhyolite. This unit, already used as a geological marker horizon because of its spherulitic texture (Piché et al. 1993), can also be used as a seismic marker horizon, essential to geophysical mapping of the deep stratigraphy and structure of the Matagami volcanic complex. By locating the Dumagami rhyolite on the seismic section, the depth of the Key Tuffite can be inferred. In addition, the stratigraphy can be established in faulted areas and where there are few deep boreholes.

Structural implications

The seismic data provide strong geometrical constraints on the attitude of faults and lithologies. The true dip of a geological sequence can be calculated (using a stereonet) from two measurements of apparent dip, since seismic reflections are located in a plane perpendicular to the lithological contacts. The units of the south flank of the Galinée anticline dip at 45° to the southwest with a strike of 130° and are continuous over a distance of 20 km (Piché et al. 1993). Therefore, the apparent dip observed on the seismic profile should be 6° on the eastern segment and 23° to the west, but the measured dips are 11° and 22° , respectively (assuming a constant velocity of 6 km/s). Lateral velocity variations or local changes in the strike directions of geological units may cause discrepancies between the expected and measured dips on the seismic section.

In the mining camp, synvolcanic faults are usually subvertical with relatively small displacements, forming a series of horst and graben structures in which the massive sulphides were trapped (C. Beaudry, personal communication, 1995). Because of their steep dip, synvolcanic faults were not imaged by seismic profiling; however, several faults are interpreted between boreholes B2 and B4 within the Lower Wabassee Group (Fig. 2.6).

The volcanic sequence was also disrupted by the subvertical Daniel fault (Piché et al. 1992). A striking feature of the seismic section is the truncation of reflections between 0.5 and 1.0 s at CMP 320 (Fig. 2.7). This sharp change in reflectivity is not a processing artifact because subtle east- and west-dipping reflections are clearly imaged on the section below 0.8 s (Fig. 2.3). Thus, the abrupt truncation of reflectors can be attributed to the juxtaposition of different lithologies and it corresponds with the proposed location of the Daniel fault (Piché et al. 1990). The fault displacement, interpreted to be 580 m, has implications for mineral exploration in the southern part of the mining camp as the Key Tuffite to the west of the fault might be at a shallower depth than originally expected. A deeper reflection (F on Fig. 2.2 and 2.7) may correspond to an east-dipping thrust fault that is projected to outcrop about 8 km to the west of the profile. A thrust fault with a similar dip has been mapped about 8 km north of line 29-3 by Beaudry and Gaucher (1986).

2.4.6 Conclusions

The Matagami seismic survey successfully imaged the sequence of steeply dipping volcanic units. Data processing had to be tailored to preserve shallow reflections when attempting to image this quasi-three-dimensional structure with two-dimensional seismic methods. In situ physical rock property measurements established that rhyolites juxtaposed against gabbros or basalts can generate strong reflections. The reprocessed section was then calibrated with available borehole geological and geophysical logs. Based on the borehole study, the Lower Wabasee Group, which directly overlies the Key Tuffite, was recognized as a marker sequence. The Dumagami rhyolite also generated a strong and continuous reflection that can be used to identify graben and horst structures that are important for mineral exploration in this mining camp. Because of their proximity to the Key Tuffite, these seismic markers are also useful

to map the depth extent of this mineralized unit. The Lower Wabasse Group is thus our key to understanding the third dimension of the Matagami mining camp.

2.4.7 Acknowledgments

Lithoprobe is a collaborative project funded jointly by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the Geological Survey of Canada. Additional funding for this survey was provided by Noranda Mining and Exploration Inc. Erick Adam acknowledges support from an NSERC scholarship and the Geological Survey of Canada. Seismic data for this experiment were collected by JRS Exploration of Calgary. Downhole geophysical measurements were conducted by Atomic Energy of Canada and by the Mineral Resources Division of the Geological Survey of Canada. We thank Pierre Verpaelt and Jeremy Hall for their constructive comments and Noranda Mining and Exploration Inc. for permission to publish this case history.

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CHAPITRE 3

A REVIEW OF HIGH-RESOLUTION SEISMIC PROFILING ACROSS THE SUDBURY, SELBAIE, NORANDA, AND MATAGAMI MINING CAMPS

3.1 Introduction

L'article de ce chapitre est intitulé "A review of high-resolution seismic profiling across the Sudbury, Selbaie, Noranda, and Matagami mining camps". Il a été publié dans l'édition de février-mars 2000 de la Revue canadienne des sciences de la Terre. Cette synthèse de tous les profils sismiques haute-résolution acquis dans le cadre du transect Abitibi-Grenville du projet Lithoprobe des régions de Selbaie, Matagami, Sudbury, et Noranda montre que l'intégration des données sismiques, pétrophysiques, et de forages profonds permet d'identifier la cause des réflexions sismiques. En particulier, les études pétrophysiques étaient la clé de l'interprétation des profils et ont permis de définir des horizons sismiques marqueurs (e.g. le "footwall complex" à Sudbury et le Groupe de Wabasse Inferieur à Matagami).

Les levés Lithoprobe haute-résolution nous montrent les premières images de la stratigraphie profonde de quatre camps miniers canadiens d'importance. Des mesures systématiques de la vitesse des ondes de compression et de la densité dans des trous

de forage profonds ont permis d'établir que les contrastes d'impédance acoustique liés aux contacts lithologiques étaient imagés, bien que des réflexions associées à des failles et à des zones de déformation ont aussi été observées. Les réflexions les plus fortes sont attribuées à des intrusions mafiques et à la présence de certains sulfures et oxydes. L'intégration des données sismiques, des mesures de propriété physique des roches et de l'information géologique a contribué à la révision de nombreux modèles géologiques et a eu un impact direct sur les stratégies d'exploration minérale à grande profondeur. L'intérêt pour les méthodes de sismique réflexion démontré par les compagnies minières s'est traduit par plusieurs études complémentaires. L'application des méthodes sismiques à la détection directe des sulfures massifs, basée sur les études de propriété physique des roches, s'est réalisée par l'entremise des technologies de sismique 2D, 3D, et de profilage sismique vertical. Le prochain défi sera d'optimiser la sismique 3D pour l'exploration minérale et d'améliorer les techniques de traitement de données afin de rehausser la réponse sismique de gisements lenticulaires profonds.

3.2 Article 2

A review of high-resolution seismic profiling across the Sudbury, Selbaie, Noranda, and Matagami mining camps

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Geological Survey of Canada contribution 1998205

Lithoprobe Contribution 1043

3.2.1 Abstract

Lithoprobe high-resolution seismic surveys have provided the first systematic images of the deep stratigraphy in four major Canadian mining camps (Noranda, Matagami, Sudbury, and Selbaie). Systematic compressional wave velocity and density measurements in deep boreholes have established that lithological contacts were the main impedance contrast imaged, although reflections from faults and deformation zones have also been observed. The strongest reflections are attributed to mafic intrusions and some sulphides and oxides. Integrating seismic, physical rock property measurements, and geological data has resulted in the revision of several geological models with direct impact on local strategies for deep mineral exploration. Mining companies have shown an interest in seismic reflection methods and this has led to several follow-up studies. The application of seismic methods to the direct detection of massive sulphides, based on physical rock property measurements, has been studied through two dimensional and three dimensional (3D) seismic imaging and vertical seismic profiling technologies. The challenge will now be to optimize 3D seismic imaging for mineral exploration and to improve seismic data processing by enhancing the seismic response from deep, lenticular orebodies.

3.2.2 Résumé

Les levés Lithoprobe haute-résolution nous montrent les premières images de la stratigraphie profonde de quatre camps miniers canadiens d'importance (Noranda, Matagami, Sudbury et Selbaie). Des mesures systématiques de vitesse des ondes de compression et de densité dans des trous de forage profonds ont permis d'établir que les contrastes d'impédance acoustique liés aux contacts lithologiques étaient imagés, bien que des réflexions associées à des failles et à des zones de déformation ont aussi été observées. Les réflexions les plus fortes sont attribuées à des intrusions mafiques et à la présence de certains sulfures et oxydes. L'intégration des données sismiques, des mesures de propriété physique des roches et de l'information géologique a contribué à la révision de nombreux modèles géologiques et a eu un impact direct sur les stratégies d'exploration minérale à grande profondeur. L'intérêt

pour les méthodes de sismique réflexion démontré par les compagnies minières s'est traduit par plusieurs études complémentaires. L'application des méthodes sismiques à la détection directe des sulfures massifs, basé sur les études de propriété physique des roches s'est réalisée par l'entremise des technologies de sismique 2D, 3D, et de profilage sismique vertical. Le prochain défi sera d'optimiser la sismique 3-D pour l'exploration minérale et d'améliorer les techniques de traitement de données afin de rehausser la réponse sismique de gisements lenticulaires profonds.

3.2.3 Introduction

High-frequency seismic reflection profiles have been acquired in various mining camps as part of the Abitibi-Grenville Lithoprobe project to test the usefulness of the method for mineral exploration. Seismic methods provide a powerful mapping tool for delineating the deep geology (>500 m) of existing mining camps, with a vertical resolution of about 30 m. Interpretations were routinely complicated by the general lack of knowledge about the reflectivity of the crystalline rocks. It became increasingly apparent that physical rock property information was needed to fully understand the nature of seismic reflectivity in the upper crust. Accordingly, comprehensive in situ measurements have been performed in numerous deep boreholes and laboratory measurements have been made on extensive sets of rock and ore samples from the Sudbury, Selbaie, Noranda, and Matagami mining camps (Fig. 3.1), demonstrating that most strong seismic reflections are caused by lithological contacts. The results to date clearly indicate that surface seismic reflection profiling, when combined with borehole geophysics, is a viable tool to map the deep stratigraphy of mining camps in two and three dimensions. Barnes et al. (1995) have presented an exhaustive appraisal of the Abitibi-Grenville seismic reflection acquisition parameters, hence seismic data acquisition is not discussed here. In each mining camp, data processing proved to be challenging and labor intensive. The success of the Lithoprobe high-frequency (up to 140 Hz) surveys has raised the interest of several mining companies, resulting in a series of follow-up studies (vertical seismic profiling, three dimensional (3D) seismic surveys, three-

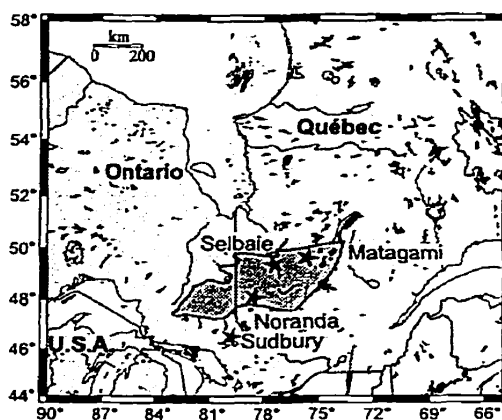


Figure 3.1: Location map of the Matagami, Selbaie, Noranda, and Sudbury mining camps in eastern Canada. The Abitibi Belt is indicated in dark grey.

component offset and 3D vertical seismic profiles) above known mineralizations. In several seismic surveys massive sulphides have been detected directly because of their high acoustic impedance. In this paper, we review case histories of integrated seismic studies in four active mining camps in Quebec and Ontario and present preliminary results from some of the follow-up surveys.

3.2.4 Seismic images of the Sudbury Structure

Questions regarding the origin of the 1850 Ma Sudbury Structure of the Canadian Shield have prompted extensive geological, geochemical, and geophysical studies for nearly a century. A first-order observation is the widespread evidence of shock deformation features that implicate a high-energy meteorite impact (Dressler et al. 1992). The Sudbury Basin is also the richest nickel-producing area in the world, with significant by-products of copper and precious metals. Nickel-rich ore is mined along the outer rim of the Sudbury Igneous Complex (SIC), a tripartite igneous sequence of norite, gabbro, and granophyre overlain by breccias and metasedimentary rocks of the Whitewater Group (Fig. 3.2). The discovery of new deposits is important for the continued use of the infrastructure of this mining district. There is significant interest in devising means to locate new nickel deposits to depths of at least 2500 m, the limit to which modern mining methods are capable of economically

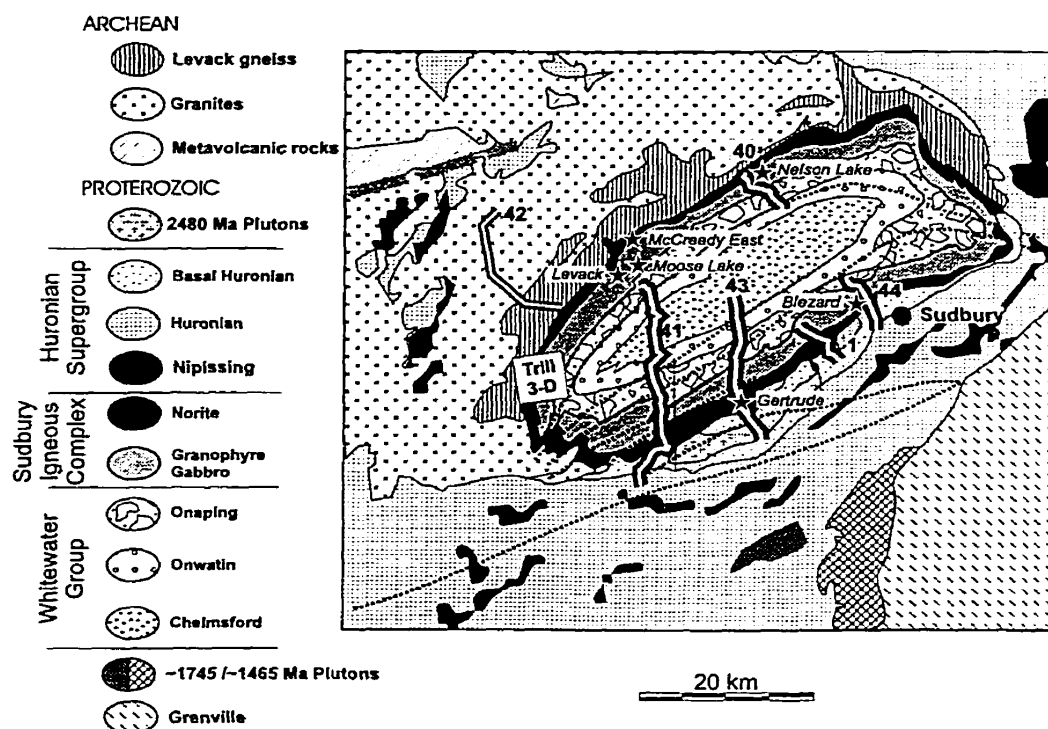


Figure 3.2: Geological map of Sudbury Structure with the location of Lithoprobe seismic profiles 40 and 41. Borehole collar locations, where geophysical logs were acquired, are indicated by the stars. The area of the 3D seismic survey is also shown (modified from Boerner et al. 2000).

extracting ore in the Sudbury mining camp.

Over the past 5 years, an extensive database of new and existing geological mapping information, geophysical logs of existing deep drill holes, and physical rock property studies on core samples has been assembled to support interpretation of two dimensional (2D) seismic data across the Sudbury Structure. In situ logging and borehole seismic experiments have been conducted at multiple locations within the SIC using full waveform sonic and density logging tools (e.g. White et al. 1994). Narrow-diameter drill holes were surveyed to depths of about 2000 m, providing superb control on the origin of reflections and the basic velocity structure of the SIC. Figure 3.3 summarizes these results, showing density and velocity logs aligned along the SIC-footwall contact. A narrow range of velocities characterizes the SIC norite, varying from 6200 to 6400 m/s, whereas the sublayer and

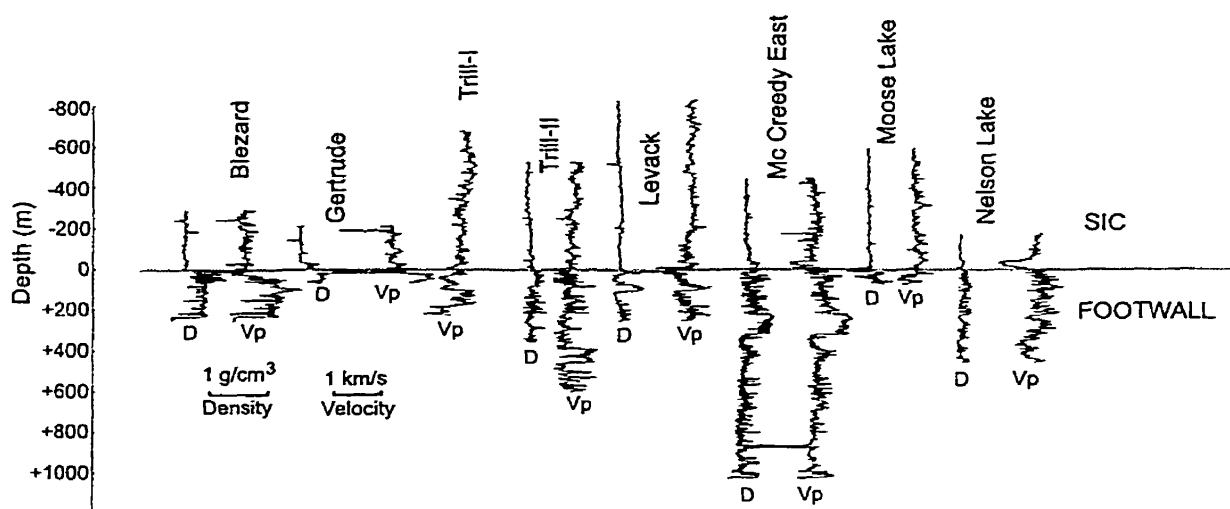


Figure 3.3: Velocity (V_p) and density (D) logs from the Sudbury Structure aligned at the contact between the norite and the footwall complex (from Milkereit et al. 1998).

footwall complex display more extreme velocity variations (6000 to 6700 m/s). Density logs follow the same trend as the P-wave velocities: relatively uniform densities between 2.75 and 2.8 g/cm³ are associated with the norite, while the sublayer and footwall complex densities range more widely between 2.75 and 3.0 g/cm³. There appears to be no lateral variation in physical properties within the SIC, nor is there a noticeable difference between the seismic properties of the North Range and South Range rocks. Consequently, the interpretation of the surface seismic data from the Sudbury Structure is well supported by basic velocity-density information. In terms of seismic exploration, the contact between the "transparent" SIC norite and the "reflective" footwall complex represents a clear regional marker horizon, making it possible to map the bottom of the SIC and the topography of the impact crater floor (the principal location for Ni-Cu deposits; Morrison, 1984).

With the high quality seismic images of the Sudbury Structure, a cross-section (Fig. 3.4) to a depth of ~15 km was obtained (Wu et al. 1995). The seismic data suggest a remarkable asymmetry of the Sudbury Structure at depth and imply that brittle thrust faulting played an important role in the northwest-southeast shortening of the structure (Fig. 3.4). The recognition of brittle deformation has direct economic implications because

it means that the ore-bearing horizon (Sudbury sublayer) may be duplicated at mineable depths in the southwest corner of the SIC (Wu et al. 1995). Also the seismic images provide evidence about the timing of deposition for major geological units. For example, there is no evidence that the thrust faults that offset the Onwatin-Onaping contact affect the Onwatin-Chelmsford contact. Thus, the deposition of the Chelmsford likely postdates brittle deformation of the SIC (Wu et al. 1995). Large lateral deviations in the seismic line azimuth have allowed for some 3D control on the lateral dip of reflectors through cross-dip analysis during data processing (Wu et al. 1995). Cross-dip analyses along seismic profiles 40 and 41, in conjunction with the structural interpretation of the seismic line (Fig. 3.4), suggest that the original center of the Sudbury Structure is now located south of the South Range (Wu et al. 1995). In Sudbury, strong reflections are interpreted to originate from lithological contacts below the North Range (White et al. 1994), whereas in the South Range prominent regional deformation zones such as the South Range shear zone have been imaged (Wu et al. 1995).

3.2.5 Selbaie

Two high-resolution seismic profiles (29-1, 29-2) were acquired at Les Mines Selbaie in the fall of 1990 as part of the Abitibi-Grenville Lithoprobe transect (Milkereit et al. 1992a). Les Mines Selbaie is a polymetallic (Cu-Zn-Ag-Au) deposit. Mineralization occurs in veins that cut the local stratigraphy at a high angle, a characteristic atypical of other base-metal deposits in the Abitibi Belt, most of which can be classified as volcanogenic massive sulfides (VMS) (Bouillon 1990). The two east-west seismic profiles (Fig. 3.5) extend for more than 6 km over the mining camp, which consists of an Archean caldera that contains primarily felsic infill (Larson 1987). The Brouillan tonalite was thrust over the volcanic sequence and subsequently cut by Proterozoic mafic dykes. The Selbaie seismic surveys were designed to map the contact boundaries of the Brouillan tonalite in the mine area and to extend this information beyond the limits of drilling to develop strategies for future mineral exploration purposes. Direct imaging of sulfide mineralization was not expected because the sulfides

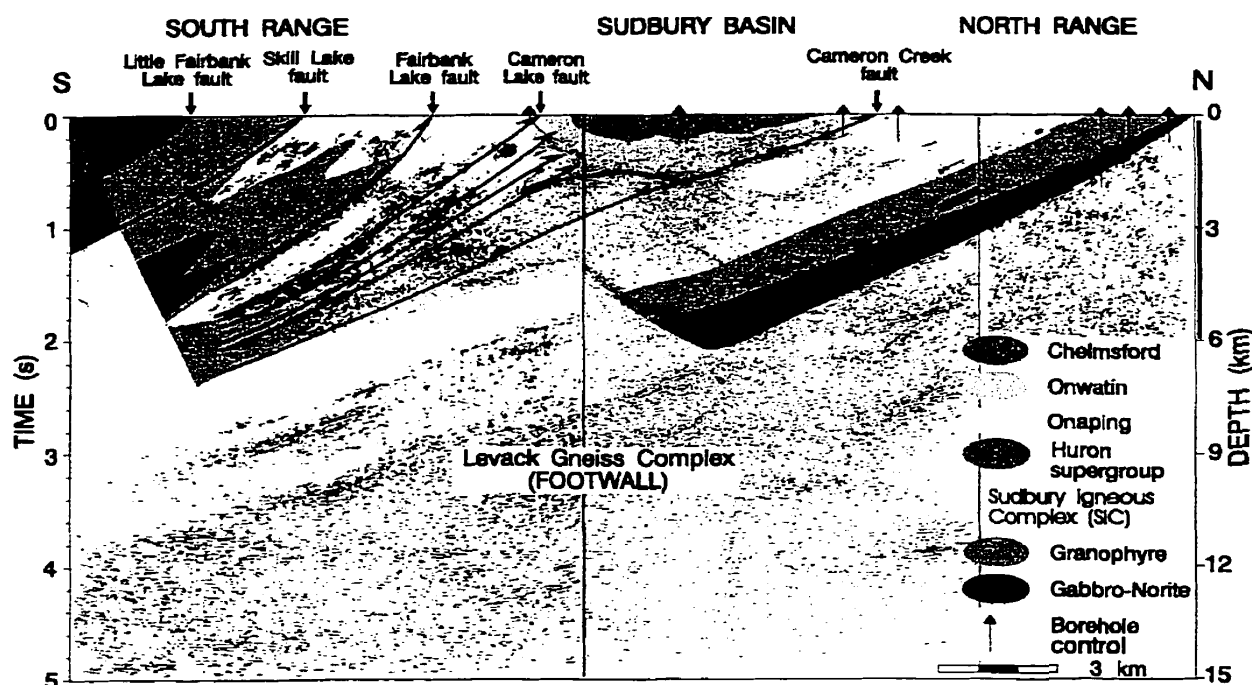


Figure 3.4: Composite north-south cross-section of the Sudbury Structure along seismic profiles 40 and 41. The overlaid interpretation reveals the asymmetry of the Sudbury Structure at depth. Reflections are interpreted to originate from lithological boundaries and deformation zones (from Wu et al. 1995).

occur in veins (Bouillon 1990).

The main challenge of this experiment was to obtain high-quality seismic images at an active mine site, where noise level are high. Indeed, shot records were badly contaminated by noise from underground workings, open-pit operations, high-voltage power lines, and the mine concentrator. These noise problems were overcome with high fold data (120) and the application of accurate refraction static corrections (Perron et al. 1997).

Reflections observed on the seismic sections were correlated to surface geological features (Milkereit et al. 1992a). The Brouillan tonalite-andesite thrust fault suture and other lithological contacts were interpreted as the main source for seismic reflections. The interpretation was further constrained by physical rock property studies. In situ gamma-gamma (density) and full-waveform sonic (velocity) measurements were collected in a deep (~1000 m) exploration borehole adjacent to seismic profile 29-2 (marked B-1219 on Fig. 3.5). Lab-

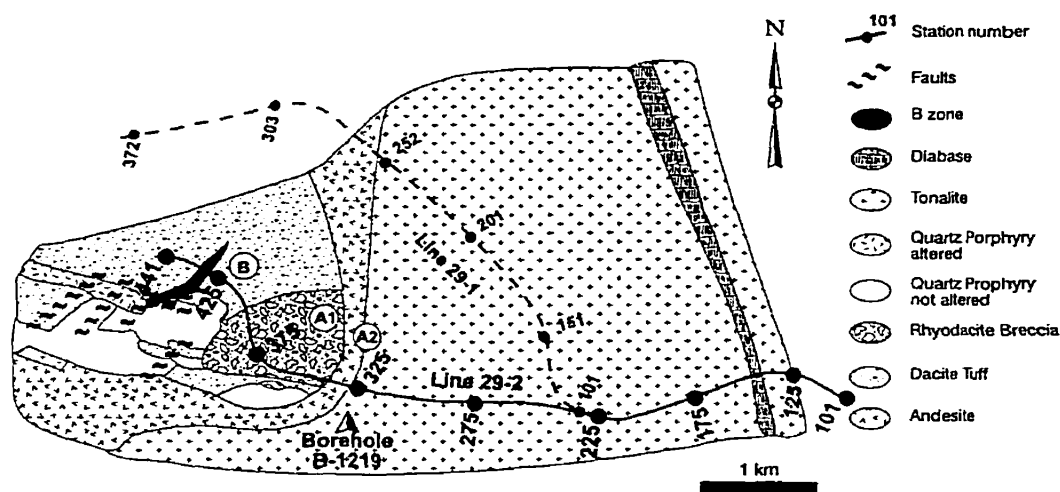


Figure 3.5: Geological map of Les Mines Selbaie and the location of Lithoprobe high-frequency seismic reflection profiles 29-1 and 29-2. Areas marked A1, A2, and B correspond to mining zones at Les Mines Selbaie (modified from Perron et al. 1997).

oratory measurements (density and velocity) were made on rock samples from the main geological units and mineralized zones in and around the mine. Integrating the physical rock properties at Les Mines Selbaie and the migrated seismic profile helped identify reflections from the Brouillan tonalite and shallow mafic dykes. Prominent reflections can be expected from contacts between tonalite and other lithological units and from mafic dykes and all other rock types (Perron et al. 1997). Laboratory analyses of rock samples also predict that sulfide bodies should give very strong reflections, given the right geometrical and geological conditions (i.e., size, shape, dip, and impedance contrast with host rocks) (Salisbury et al. 1996). Unfortunately, only the last condition was met at Les Mines Selbaie.

Even though direct detection of massive sulfide veins was not possible, the two surveys were able to produce images of key horizons such as the east-dipping Brouillan tonalite contact and possibly the extension of the westernmost mineralized zone (marked III on Fig. 3.6) beyond the limit of drilling (see Fig. 3.6). Results from these profiles were also used to place constraints on the major tectonic events that took place at Les Mines Selbaie. The sequence of events interpreted from the geometry of reflectors suggests that the volcanic stratigraphy was truncated by thrusting of the Brouillan tonalite (marked I on Fig.

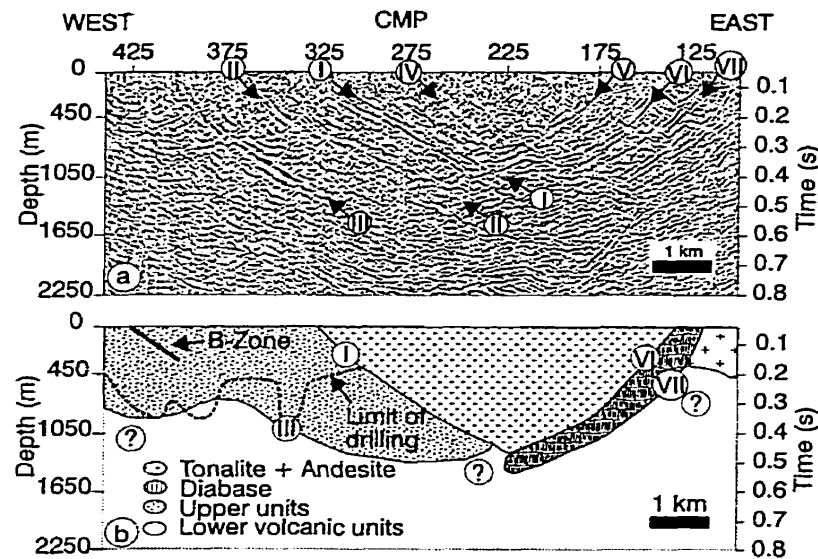


Figure 3.6: Geologic interpretation (b) of migrated seismic data (a) from profile 29-2 across Les Mines Selbaie. Reflection I projects into the fault-bounded tonalite-andesite contact. Within the volcanic sequence, reflection II is interpreted as a lithological contact between mafic dykes and dacitic tuff-rhyolite. Reflection III is interpreted as the floor of the volcanic complex. At the eastern end of line 29-2, reflections VI and VII may define the top and bottom of a moderately to steeply west-dipping diabase dyke. VII is also interpreted to represent the easternmost extension of the volcanic complex (modified from Perron et al. 1997).
CMP, common midpoint.

3.6). The west-dipping diabase intrusion is believed to mark the westernmost limit of the volcanic complex and to crosscut older units (i.e. tonalite and caldera infill). These results corroborate the geochronological data of Barrie and Krogh (1996) which suggest that at first a transgressive, stratiform to epithermal mineralizing system formed within a calc-alkaline, volcanic-plutonic suite at 2725-2730 Ma (caldera stage), the peak of volcanic activity in the northern Abitibi subprovince. This event was followed by west-directed thrusting over the mineralization (thrusting of the Brouillan tonalite), resulting in fluid movement and partial to complete regrowth of zircon and resetting of the U-Th-Pb systematics within the fault at ~2.69 Ga. The seismic survey also imaged a Proterozoic diabase intrusion at the eastern end of the profile.

3.2.6 Noranda mining camp

The Noranda mining camp is located in the Blake River Group (BRG) of the Abitibi subprovince and in the world's largest greenstone belt. The BRG is the most extensive volcanic sequence found in the southern Abitibi Belt and is dominated by the economically important Noranda central volcanic complex (CVC). To date, 35% of the gold, 53% of the silver, 48% of the copper, and 21% of the zinc has been extracted from the CVC part of the Abitibi Belt (Simard et al. 1990). The volcanic stratigraphy of the CVC consists of a bimodal sequence of rhyolite and andesite flows cored by the Flavrian pluton. The whole structure is cross-cut by diorite dikes and sills. Acquisition of Lithoprobe high-resolution data in the Noranda central camp took place in 1988 (line 14b) and in 1990 (line 21-1) (Fig. 3.7). Seismic line 14b strikes north-south across the Larder Lake-Cadillac fault, Rouyn-Noranda, and ends approximately 5 km north of the Lake Dufault granodiorite (Fig. 3.7). Seismic profile 21-1 was acquired across the CVC of the BRG in an east-west direction (Fig. 3.7). Part of this profile crosses the Ansil mining site. The 1990 survey benefited from superior data acquisition technology compared to that used in 1988. The use of a digital telemetry system with digitization at the receiver station resulted in improved data quality and superior noise suppression (less susceptibility to 60 Hz contamination and elimination of signal amplitude and phase distortion).

An initial laboratory physical rock property study (density and compressional-wave velocity) (Adam et al. 1992) of 16 samples indicated that mafic intrusives (metagabbro, metadiabase, and diabase) had high acoustic impedances. On the basis of the laboratory studies, reflection coefficients as high as 10% were expected at the contact between felsic volcanic rocks and mafic intrusions. In situ density and compressional-wave velocity measurements were performed in a 1677 m deep borehole located 50 m from seismic line 21-1, and densities were measured on core samples from two additional boreholes (Verpaelst et al. 1995). The diorites had the highest acoustic impedances ($\sim 23 \cdot 10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$) and rhyolites the lowest ($\sim 18.5 \cdot 10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$) (Verpaelst et al. 1995). The acoustic impedance of basalts was about $20.5 \cdot 10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$, and thus only weak reflections were

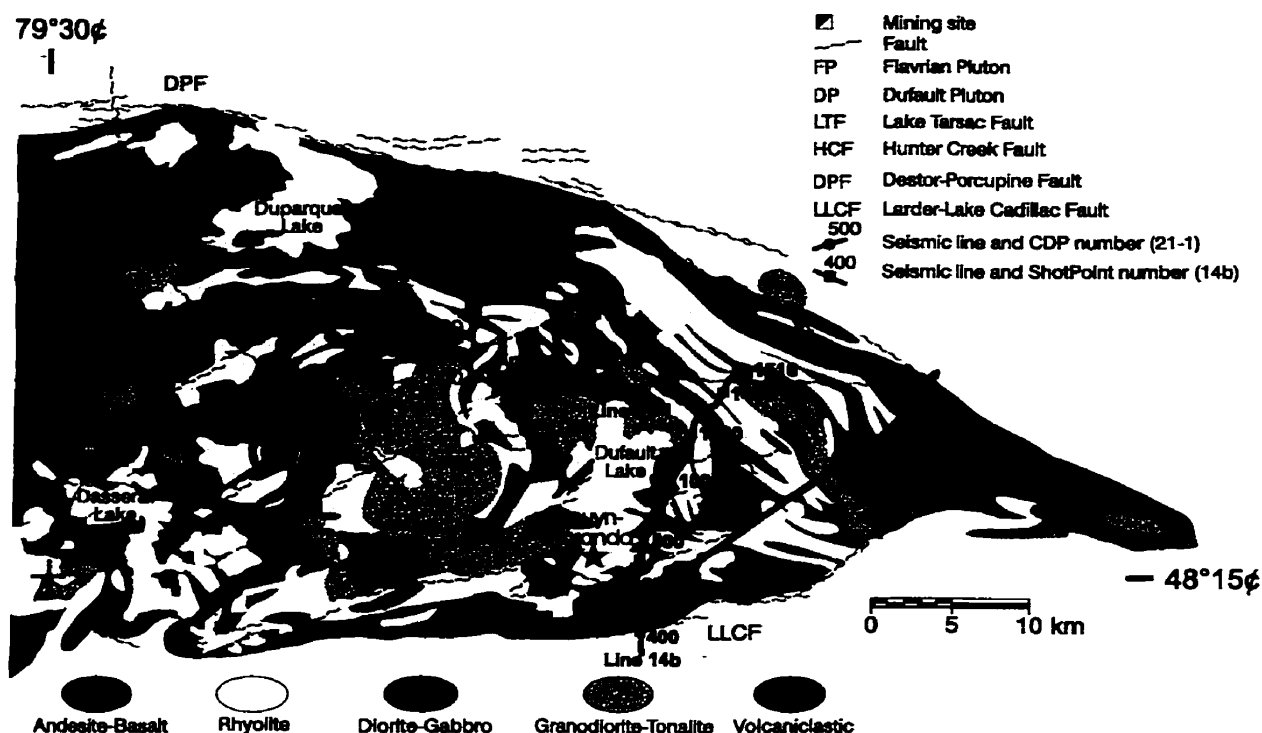


Figure 3.7: Geology of the Blake river Group of Western Quebec. The location of high-frequency Lithoprobe seismic profiles 21-1 and 14b are indicated (modified from Perron and Calvert 1998).

expected from contacts between mafic and felsic volcanic units. Densities were measured on a total of 412 core samples (Verpaelt et al. 1995), and a statistical analysis of the diorite densities revealed a bimodal distribution. The high-density population correlated with iron-rich diorites, thus exhibiting high acoustic impedances compared with other diorites. Based on the petrophysical studies, the strongest reflections in the Noranda mining camps should occur at the contact between rhyolites and iron-rich diorites.

Figure 3.8 shows the superposition of a geological interpretation of the Ansil mine based on borehole data and the high-frequency seismic profile. Discrepancies between the borehole information and the seismic data can be caused by local variations of strike of reflecting lithological contacts appearing as out-of-plane events, and scattering from geological features located on either side of the seismic profile can also contaminate the seismic section. These effects must be kept in mind when the geological section derived from borehole infor-

mation and the seismic data are compared. Weak reflections are observed between volcanic rocks as predicted from the rock property studies. Most of the strong reflections are associated with dioritic intrusions, which are easier to image with seismic reflection methods because of their geometry, cutting through existing rocks in sheet-like surfaces. The nature of the contacts between the different volcanic units is probably more complex, and perhaps related to the way successive lavas were erupted and subsequently cooled to produce contacts that are laterally heterogeneous at seismic scales of investigations (Perron and Calvert 1998). The rocks of the Flavrian pluton are spatially distributed as a series of sub-horizontal tabular sills that form a genetically related group. Early fracture systems in the pluton developed in response to strain caused by regional deformation. These fractures were precursors to the emplacement of diorite sills. The presence of diorites is interpreted as evidence of an episode of subvertical extension sustained by the layered Flavrian pluton. At the Pierre-Beauchemin gold mine, mineralization is associated with these concordant layered dioritic intrusions (Richard et al. 1990). Because of their high acoustic impedance, these dioritic intrusions appear in the seismic image, permitting interpretation of the shape and internal structures of the Flavrian pluton (Perron and Calvert 1998).

3.2.7 Matagami mining camp

The Matagami mining camp forms part of the volcano-sedimentary Harricana-Turgeon belt in the northwestern part of the Abitibi subprovince (Lacroix et al. 1990). The Matagami volcanic complex of the northern Abitibi Belt was formed by two major phases of volcanism: the early phase produced rhyolites of the Watson Lake group (Fig. 3.9), and the second one was dominated by basaltic volcanism and formed the Wabasse Group (Beaudry and Gaucher 1986). A cherty, sulphidic chemical sediment known as the Key Tuffite marks the contact and hiatus between the groups. This thin horizon (0.6-6 m) is the primary exploration target because it hosts most of the orebodies discovered in the camp (Piché et al. 1993). The volcanic rocks are folded in an open, gently northwest-plunging structure known as the Galinée anticline (Sharpe 1968). Rocks on the south flank of the anticline,

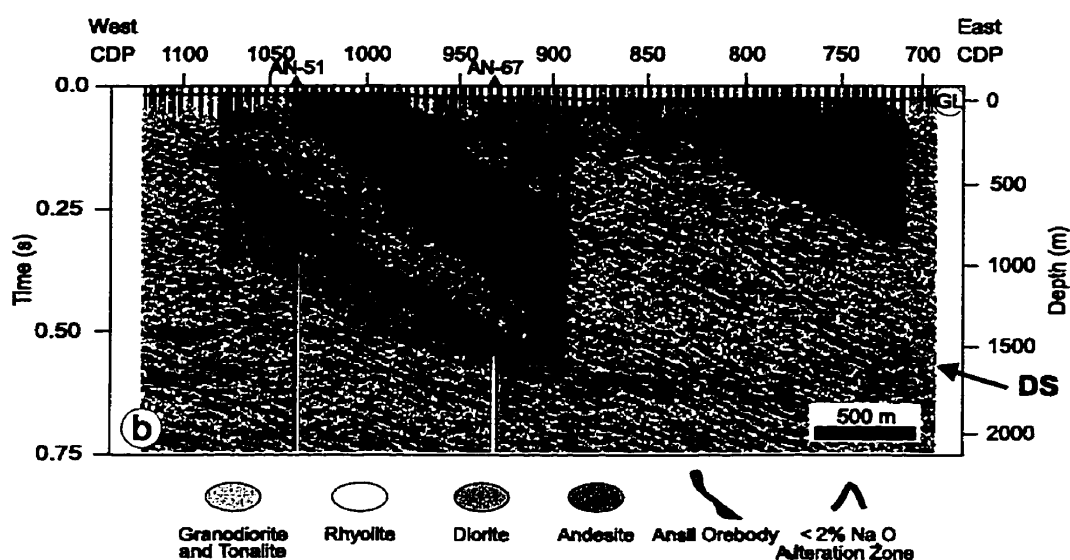


Figure 3.8: Seismic section (line 21-1) over the Noranda central camp near the Ansil mine with the geological crosssection derived from borehole data superimposed. The boreholes used to constrain the geological crosssection are indicated by the vertical red lines. DS, a long, continuous reflection that extends directly into a diorite sill in the geological model (modified from Perron and Calvert 1998); GL, ground level; CDP, common depth point.

where our study area is located, are weakly deformed and dip approximately 45° towards the southwest (Piché et al. 1993). Bell Allard is a typical Matagami camp south flank deposit. It is located at the Watson-Wabasse interface atop a synvolcanic fracture zone characterized by classic hydrothermal alteration. A weakly transposed concordant lens of sulphide mineralization directly overlies a discordant pipe, or conduit, hosting massive to stringer mineralization. The orebody is approximately 370 m long, and is 165 m wide in the downdip direction. Sulphide mineralization consists of pyrite, Fe-rich sphalerite, minor chalcopyrite, and pyrrhotite. Thickness averages 30 m, but can range up to 60 m in portions of the south lens. The deposit dips 50 to 55° towards the south between depths of 900 and 1150 m. The production decision was based upon a drilling-indicated reserve of 3.2 million tonnes grading 13.77% Zn, 1.50% Cu, 43.45 g/t Ag, and 0.76 g/t Au.

Two high-resolution Lithoprobe seismic profiles (lines 29-3 and 93a) were acquired at the Matagami mining camp (Fig. 3.9). The objective of the first survey, acquired in 1990, was to

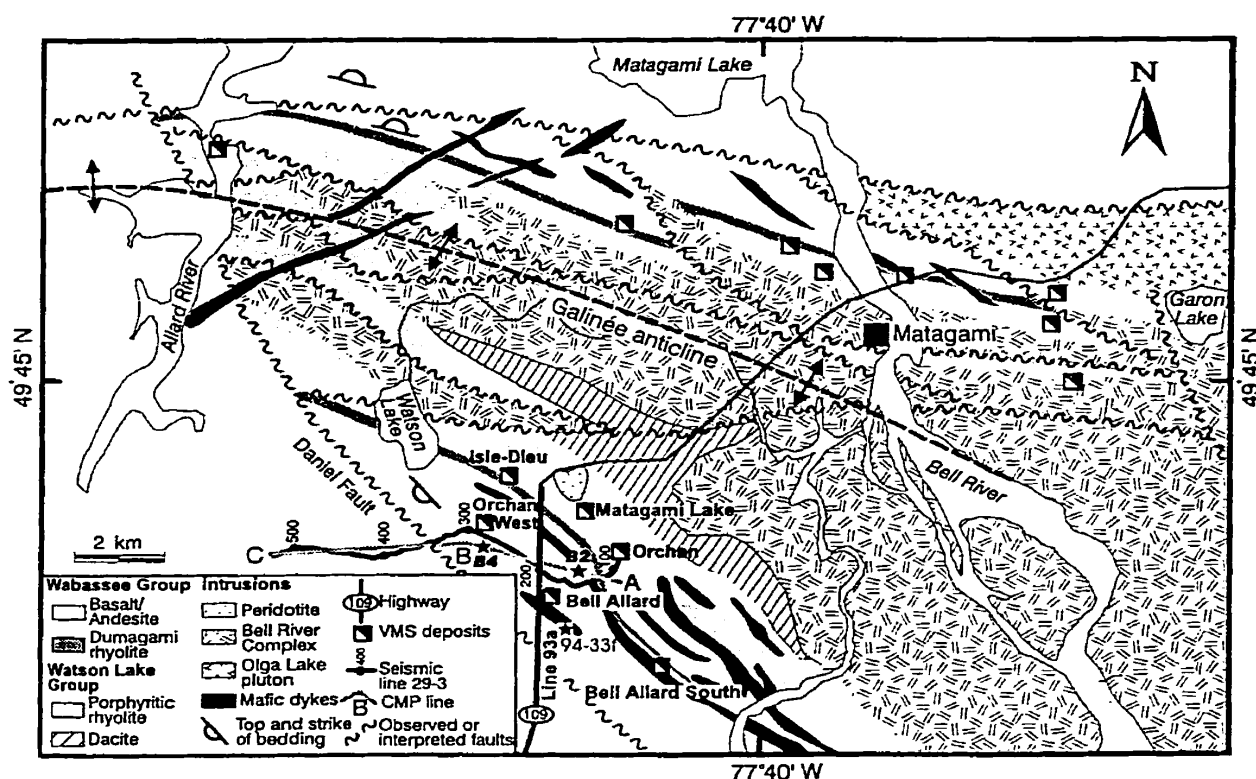


Figure 3.9: Geological map of the Matagami mining camp showing main lithological units, location of seismic profile 29-3 and location of boreholes (B2, B4) used to constrain the interpretation. The CMP line used for processing is also indicated (A, B, and C) (from Adam et al. 1998b).

map the contact between the mafic Wabasse Group and the felsic Watson Lake Group west of the Daniel fault where borehole control was unavailable. In 1993, a second Lithoprobe seismic profile (line 93a) was acquired above the newly discovered Bell Allard deposit to test the possibility of detecting directly deep volcanogenic massive sulphide orebodies using seismic reflection technology.

To aid in the interpretation of the seismic data and to better understand the high reflectivity of the volcanic sequence, a comprehensive physical rock property study was undertaken using both in situ (Milkereit et al. 1992b; Adam et al. 1998b) and core sample measurements (Adam et al. 1996). Results of this study are summarized in Fig. 3.10. Rhyolites exhibit the lowest acoustic impedances whereas the highest are attributed to pyrite-rich sulfides. Magnetite-rich gabbros also have high acoustic impedances. In general, basalts

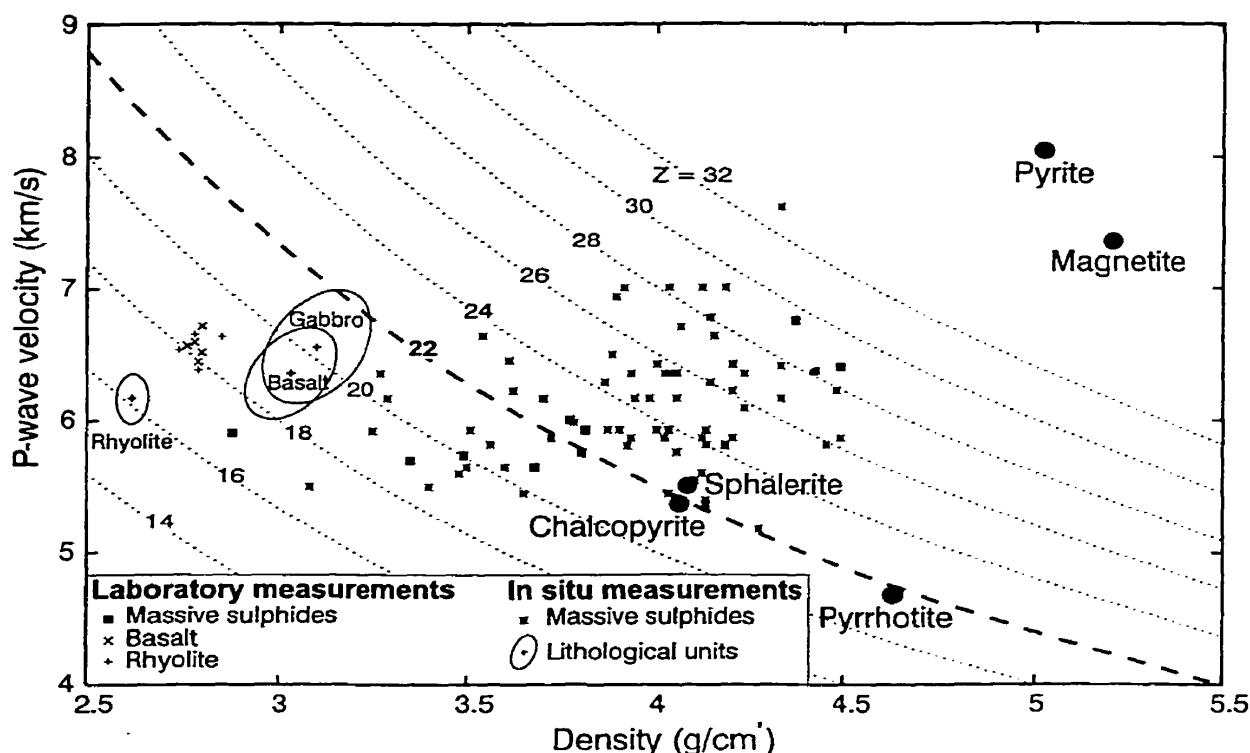


Figure 3.10: P-wave velocities and densities in the Matagami mining camp from logging the hosts rock in hole 94-33f, and massive sulphides in hole 94-26a. Also shown are laboratory data from core and samples from the Bell Allard and Isle-Dieu orebodies. The dashed lines show iso-impedance (Z) contours in units of $10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$. Most of the volcanic units (95%) have acoustic impedances (Z) below $22 \cdot 10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$, and most of the sulphides have impedances above $22 \cdot 10^5 \cdot g \cdot cm^{-2} \cdot s^{-1}$. Ellipses around lithologic units (gabbro, basalt, rhyolite) show 1 standard deviation (from Adam et al. 1996).

and gabbros have similar acoustic impedances and no reflections are expected between these two rock units in the Matagami mining camp. On the other hand, strong reflections are expected from the contacts between rhyolites and magnetic gabbros or pyrite-rich massive sulphides.

Figure 3.11 shows the final migrated stacked section of profile 29-3 (Adam et al. 1998b). Strong reflectivity associated with the Lower Wabasse Group is due to the presence of rhyolite units in a generally mafic sequence. This reflective package, which directly overlies the mineralized contact (marked as Key Tuffite on Fig. 3.11), can be used to map the

deep stratigraphy of the mining camp. The seismic profile has successfully delineated the mineralized contact from a depth of 500 m to about 3 km at the western end of the seismic profile (at C). Determination of the strike and true dip of a geological unit can be inferred (using a stereonet) from seismic profiles acquired along two different directions. The change of azimuth of the seismic profile (B on Fig. 11) allows the determination of the true attitude of the Key Tuffite. The units of the south flank of the Galinée anticline dip at 45° to the southwest with a strike of 130° and are continuous over a distance of 20 km (Piché et al. 1993). Therefore, the apparent dip observed on the seismic profile should be 6° on the eastern segment and 23° for the western segment. The measured dips of 11° and 22° , respectively (assuming a constant velocity of 6 km/s), are in good agreement with the estimated apparent dip calculated using the regional strike and dip values. The location and throw of the Daniel fault, a major fault marking the western limit of the mining camp, were estimated from the truncation of the Lower Wabassee Group reflective package. The vertical displacement caused by the Daniel Fault is estimated to be 500 m (± 100 m). The fact that the vertical displacement is less than 1 km as initially anticipated (C. Beaudry, personal communication, 1995) has a direct implication for mineral exploration west of the fault because the mineralized horizon could be at mineable depths.

Lithoprobe line 93a was acquired directly above the Bell Allard deposit. The 6 million tonne sphalerite-rich ore deposit lies between depths of 900 and 1150 m from surface (Adam et al. 1996). The seismic section, obtained by prestack migration, shows a detailed image of the volcanic stratigraphy, and the gabbro sills that intrude it (Calvert and Li 1999). Faulting can be inferred from discontinuities in these reflections (Fig. 3.12a), though the exact position of the faults in three dimensions is unclear because the seismic profile is oblique to the predominant dip direction of the Galinée anticline. The location of the contact between the Lower Wabassee and the Watson Lake groups is interpreted on the seismic section parallel to the reflections from the volcanic stratigraphy and at a depth defined by borehole data and the intersection with line 29-3. A strong reflection originating from the top of the Bell Allard deposit is identified at the intersection of a low-angle normal fault with the top

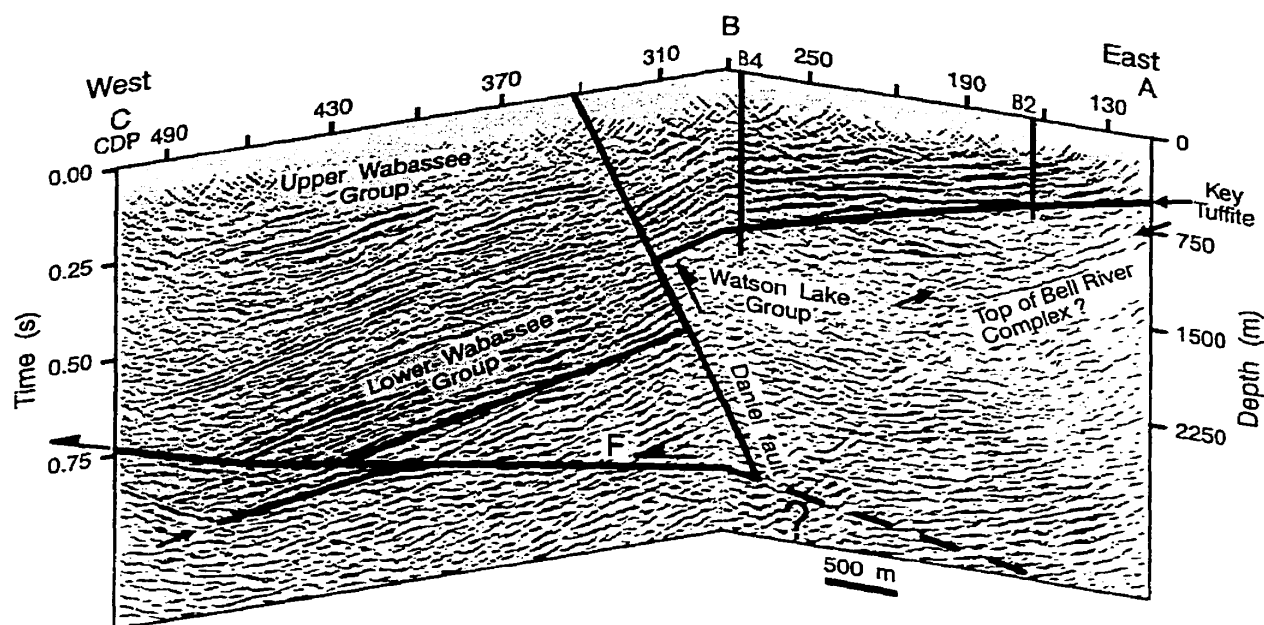


Figure 3.11: Migrated fence diagram of line 29-3 in the Matagami mining camp. The main geological units and faults are indicated. The Key Tuffite is located at the base of the reflective Lower Wabasse Group. Note that the approximate depth scale has been calculated using a 6 km/s average crustal velocity. Control provided by drillholes B2 and B4 (from Adam et al. 1998b).

of the Watson Lake Group (Fig. 3.12b), indicating that sulphide mineralization may have been controlled by fluid flow along the fault, which likely penetrates to the underlying mafic intrusion. The reflection from the orebody does not appear to extend over its full width as defined by drilling, but seems to correspond to the lower pyrite-rich zone. Although the ore body reflection is strong, it is of comparable amplitude to other reflections recorded in the mining camp, particularly those from the gabbro sills.

3.2.8 Beyond seismic profiling

Deep borehole information, in situ logging data and laboratory physical rock property measurements, and Lithoprobe seismic data, have shown that lithological contacts are the principal cause of reflections in mining camps. Physical rock property studies also indicate that sulphides and oxides, in particular pyrite and magnetite, exhibit anomalously

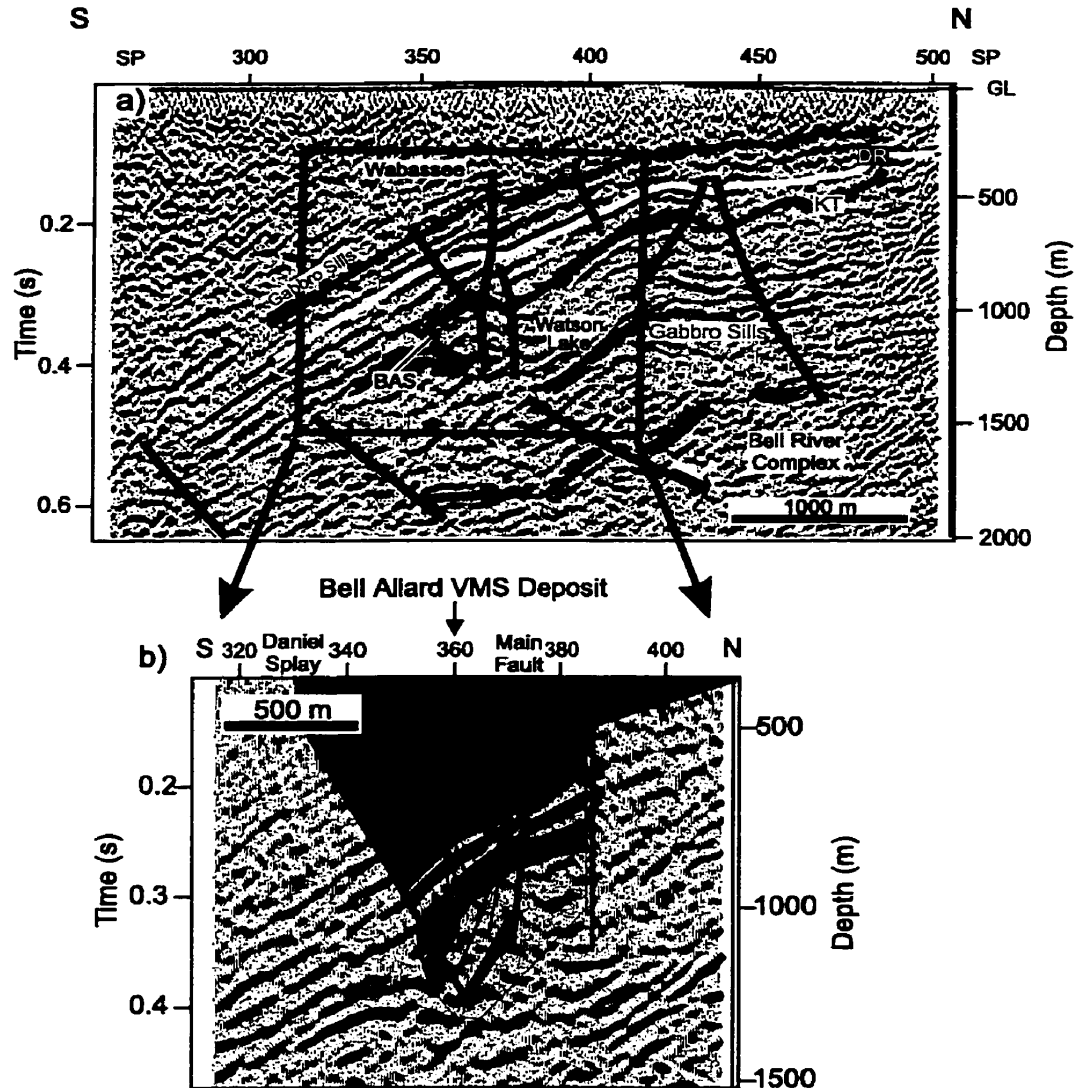


Figure 3.12: (a) Interpreted prestack migrated section of line 93a. Strong reflections are associated with gabbro sills and interlayered rhyolites and basalts within the Lower Wabassée Group. BAS, Bell Allard sulphides; DR, Dumagami rhyolite; KT, Key Tuffite. (b) Detailed seismic data and geology from the vicinity of the Bell Allard deposit (modified from Calvert and Li 1999).

high acoustic impedances (Adam et al. 1996; Salisbury et al. 1996). Hence, massive ore deposits should also generate strong reflections, but they often have irregular or unpredictable geometries with complex internal layering and composition. Numerical modelling studies (Eaton 1999) show that simple and homogeneous lenticular orebodies appear as hyperbolic events (diffractions) on unmigrated seismic sections with the highest amplitudes located in the downdip direction of the lens. High-amplitude diffraction hyperbolas observed above the Creighton mine in Sudbury (Milkereit et al. 1996) confirm the physical rock property and numerical modelling studies. Further evidence of reflections from sulphide bodies is seen in vertical seismic profiles (VSP) acquired in boreholes intersecting mineralized zones (Adam et al. 1996; Salisbury et al. 1997). VSP data are acquired by placing receivers at regular depth intervals in a borehole and a fixed source located at the surface. VSP survey geometries provide not only an accurate time-to-depth conversion, but also a direct and unambiguous link between seismic reflections and the geological features intersected by the borehole. VSP recordings at the Bell Allard deposit in Matagami (Adam et al. 1996) and at the Halfmile Lake deposit in Bathurst (Salisbury et al. 1997) have revealed that the strongest reflections originate from orebodies (e.g., Fig. 3.13). At Bell Allard, reflections from contacts between mafic and felsic volcanic units (rhyolite-basalt) were much weaker than the reflection from the orebody contact.

Orebodies comparable in size to the dominant seismic wavelength tend to scatter, not reflect, seismic energy. In these cases, seismic profiles do not allow discrimination between point scatterers (the orebodies) and scattering from linear geological structures (e.g., lithological contacts intersected by a fault). Furthermore, anomalous high-angle refracted reflections occur at the boundary between the homogeneous high-velocity field (~ 6 km/s) of the crystalline rocks and the low-velocity (< 1.5 km/s) overburden allowing imaging of structures from the side of the profile (e.g., Zaleski et al. 1997). In other words, in areas of thick, low-velocity overburden, surface vertical geophones become omnidirectional. Thus, the 2D seismic reflection method is of limited use in defining drilling targets because with a straight seismic line it is impossible to determine the direction of the seismic waves.

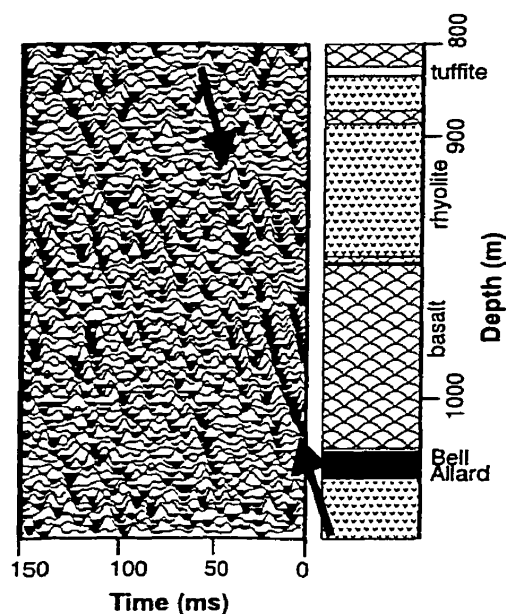


Figure 3.13: Portion of the VSP section obtained in Bell Allard hole 94-33f between 800 and 1065 m depth. Note the high-amplitude reflection (arrows) associated with the Bell Allard sulphides (from Adam et al. 1996).

To overcome the limitations of 2-D seismic, 3-D seismic technology has been tested by Inco, Falconbridge, Noranda, and the Geological Survey of Canada on the Trillabel property (Sudbury) and on the south flank of the Galinée anticline (Matagami). Both surveys had similar objectives, the direct detection of massive sulphide orebodies, but presented different data acquisition and processing challenges. The Matagami region is characterized by a variable thickness overburden but has relatively minor topographical variations, whereas the Sudbury sites had steep hills, swamps, and limited access (Milkereit et al. 1997). These differences translated into different 3D seismic acquisition grids. For both surveys, the low signal-to-noise ratios due to the weak reflectivity between geological units and the moderate to high dips of the major geological structures (30 to 60°) demanded recordings with large source-receiver offsets and the use of high-fidelity recorders (24 bit) with large channel capacity (2000). The 3D seismic surveys were acquired above known magmatic Ni-Cu (Trillabel, Sudbury) and typical Zn-Cu volcanogenic massive sulphide (Bell Allard, Matagami) deposits. In both cases the known mineralization generated distinctive seismic anomalies in

the 3D volumes (Adam et al. 1998a; Milkereit et al. 1997). Circular amplitude anomalies centered on the known orebody location are observed on timeslices (horizontal slices through the 3-D data volume) (Fig. 3.14). This response is observed on unmigrated data and it appears that prestack and poststack migration partly or completely destroy the orebody response. There are at least two factors which may produce this result: (1) shape dependant seismic amplitude variations and phase reversals caused by the dipping lens and (2) the enhancement of dipping reflections which obscure the orebody response. Nonetheless, 3D seismic technology is still the best seismic method to map deep stratigraphy accurately and to locate point scatterers in the subsurface. Our experience also shows that data acquired using standard techniques and equipment, and processed with available commercial software, can produce high-quality seismic images. Data interpretation packages developed for the oil and gas industry were useful for integrating existing surface and subsurface data with the seismic data.

3.2.9 Discussion

The depth penetration and resolution of surface seismic reflection methods make them an attractive means by which to map geological structures and possibly detect orebodies at depths greater than 500 m. However, interpreting 2D seismic profiles acquired above complex geology is difficult because, in many cases, the seismic profile does not represent a vertical section through the Earth. For seismic lines that are not recorded perpendicular to the strike direction, reflections occur at locations, which are offset laterally from the profile (side swipe). The distance from the profile at which the reflections occur depends on the geological strike and dip with respect to the orientation of the seismic line. Thus, data interpretation must take into account the geometrical factors as well as constraints implied by information from deep boreholes and the physical rock property studies. Defining drill targets based on a set of 2D seismic profiles in an area of complex geology is a difficult task because it is almost impossible to discriminate between point and linear scattering without a true 3D seismic image. Crooked line seismic profiles generate a lateral scattering of the

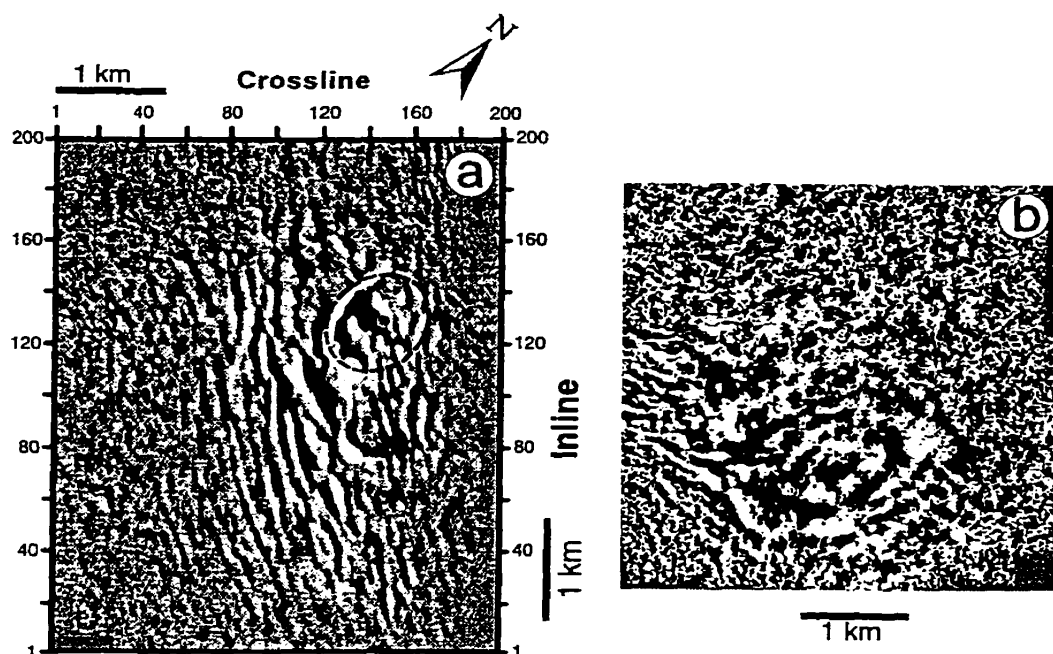


Figure 3.14: (a) Timeslice (at 410 ms) from unmigrated Matagami 3-D stacked data. The circular anomaly exhibits a clear amplitude versus azimuth anomaly characteristic of the seismic response from a dipping lens. The grey dot at the center of the circular anomaly corresponds to the location of the Bell Allard orebody. (b) Scattering response as seen by 3-D seismic time slice (790 ms) from the Trill area in Sudbury (modified from Adam et al. 1998a and Milkereit et al. 1998).

midpoints resulting in some pseudo-3D subsurface coverage. Processing these datasets using nonstandard processing techniques (e.g., cross-dip corrections) or by processing them as a small 3D survey (Wu et al. 1995) gives more information than seismic data acquired on a straight line. Nonetheless, because of its limited imaging capacity, the 2D seismic reflection method should be used in areas of relatively simple geology and to test 3D data acquisition parameters.

Estimating the position of a reflector in a hard rock environment is possible using 3D seismic technology (Adam et al. 1997; Milkereit et al. 1997; Pretorius et al. 1997). The advantage of the method is that acquisition, processing and interpretation techniques are standard and commercially available. Yet, to achieve sufficient coverage (fold), 3D seismic surveys need to be more than about 16 km² in size. Due to their large size and cost,

3D seismic surveys may be too expensive for solving small-scale geological problems or for exploring smaller prospects. The challenge is thus to reduce the cost of 3D seismic reflection surveys or to find alternative approaches better suited for the smaller prospects.

Several alternative methods are available to produce 3D seismic images: 3-D VSP, offset VSP, and "side-scanning." The latter method was tested on the Kidd Creek property by Eaton et al. (1997). This study showed that by using receivers placed in a borehole with a line of shots at the surface, it was possible to map vertical contacts and even locate a massive sulphide lens. The imaging area of about 1 km² is more compatible with the size of mining prospects. Since 1997, the Downhole Seismic Imaging (DSI) Consortium (GSC, Falconbridge, Inco, Noranda, and several Canadian universities) has been studying the use of downhole receivers and surface sources for the purpose of directly detecting massive sulphides using VSP technology. The development of a cost-effective alternative to standard 3D seismic surveys, while producing well-documented case histories, may facilitate the integration of seismic methods into the normal exploration procedures for deep base metal deposits in established and prospective Canadian mining camps.

3.2.10 Conclusions

Integration of seismic data, physical rock property data, and deep borehole information in four Canadian mining camps has given new insights into the nature of seismic reflectivity in the upper crust. Clearly, lithological contacts are the main source of the observed seismic reflectivity. Due to their high acoustic impedance against host rocks, mafic intrusions and mafic volcanic flows are prime candidates to generate strong reflections. In all mining camps, the physical rock property studies were the key to understanding the seismic reflectivity and interpreting the seismic data. The recognition of seismic marker horizons (e.g., the footwall complex in Sudbury, the Lower Wabasee Group in Matagami) is a major step towards the implementation of reflection seismic technology for mapping the deep geology of the mining camps.

Evidence from physical rock property studies of ores, and VSP, 2D, and 3D surveys sug-

gests that the direct detection of deep massive sulphide orebodies is possible. Technology available today for data processing and data acquisition appears adequate to allow integration of reflection seismic methods into normal exploration procedures. More efforts will be required to enhance the scattering response of lens-shaped orebodies and to optimize 3D seismic data acquisition. Follow-up studies are being undertaken at the Geological Survey of Canada, in collaboration with major Canadian mining companies and universities, to study the possibility of directly detecting massive sulphide deposits at depths exceeding 500 m.

3.2.11 Acknowledgments

Lithoprobe is a collaborative project funded jointly by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the Geological Survey of Canada. Additional funding for the mining camp seismic surveys was provided by Noranda Mining and Exploration Inc., Falconbridge, Inco, Ministère de l'Énergie et des Ressources du Québec, and Ontario Geological Survey. Erick Adam acknowledges support from an NSERC scholarship. Constructive suggestions by David Eaton, Christopher Juhlin, and Brian J. Todd helped to improve the final manuscript. Downhole geophysical measurements were conducted by Atomic Energy of Canada, the Mineral Resources Division of the Geological Survey of Canada, and the University of Alberta.

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CHAPITRE 4

VERTICAL SEISMIC PROFILING AT THE BELL ALLARD OREBODY, MATAGAMI, QUEBEC

4.1 Introduction

Ce chapitre se compose de l'article intitulé "Vertical seismic profiling at the Bell Allard orebody, Matagami, Quebec". Il a été soumis en avril 2000 pour publication dans le livre "Hardrock seismic exploration methods" édité par B. Milkereit, D. Eaton, et M. Salisbury et publié par la "Society of Exploration Geophysicists". Ce chapitre démontre que le gisement Bell Allard produit une forte réflexion sismique. Des simulations numériques pour optimiser l'utilisation des PSV en exploration n'ont pas été concluantes. Les paramètres utilisés pour la modélisation font que les amplitudes maximales des réflexions des sections PSV synthétiques dans des trous de forage situés à des distances de 200 m et de 700 m sont faibles.

Deux profils sismiques verticaux (PSV) ont été effectués aux environs du dépôt de sulfures massifs volcanogènes (VMS) Bell Allard enfoui à 1 km de profondeur dans la sous-province de l'Abitibi du nord-ouest québécois. Les données PSV révèlent que la vitesse moyenne de l'onde de compression (P) dans le premier kilomètre de la croûte est d'environ 6300 m/s alors que la vitesse de l'onde de cisaillement (S) est estimée à 3600 m/s. La concordance entre la vitesse moyenne obtenue des données PSV et celle dérivée de la diaggraphie sonique, confirme la précision des deux méthodes. L'un des PSV intersecte la lentille de sulfures

massifs et a enregistré une forte diffraction de l'onde P et une onde S convertie provenant du gisement. Le second PSV, situé à plus de 200 m au nord ouest du dépôt, a imagé un contact basalte-rhyolite. Cependant, aucune diffraction provenant des sulfures massifs n'a été identifiée. La modélisation numérique montre que le gisement de Bell Allard génère une forte diffraction de l'onde P et une conversion en onde S. Toutefois, les amplitudes décroissent considérablement en fonction de la distance et montrent une forte variation selon la distance et l'azimuth. Pour les dépôts de forme complexe, la position optimale du point de tir d'un PSV dépend de la profondeur, du pendage, et de l'orientation de la cible. L'utilisation d'une grande séparation entre le point de tir et les récepteurs en trou de forage peut être nécessaire pour détecter des dépôts SMV de forme complexe et dont le pendage est modéré.

4.2 Article 3

Vertical seismic profiling at the Bell Allard orebody, Matagami, Quebec

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4.2.1 Abstract

Two vertical seismic profile (VSP) surveys have been acquired in the vicinity of a 1 km deep volcanogenic massive sulphide (VMS) deposit in the Abitibi subprovince of northwestern Quebec. The VSP data show that average P-wave velocities of the top 1 km of the crust around the orebody are ~ 6300 m/s and S-wave velocities are estimated at ~ 3600 m/s. The agreement (within 0.3%) between the average velocity derived from VSP and sonic logging data confirm their accuracy. One VSP survey intersected massive sulphides and recorded a strong P-wave and a converted S-wave scattered from the ore deposit. The second VSP survey, located about 200 m to the northeast of the deposit, imaged a basalt-rhyolite contact; however, no prominent scattered events from the ore zone were observed. Seismic modelling demonstrates that the VMS deposits of the Matagami mining camp generate strong scattered P- and converted S-waves. However, the amplitudes decrease significantly with distance and exhibit strong variations with offset and azimuth. For complex shaped orebodies the optimum shot location depends on the target's depth, dip and strike as well as the receiver location. Large offsets between shot and downhole receivers may be necessary to image complex, moderately dipping VMS deposits.

4.2.2 Introduction

An early application of VSP was to convert seismic time to depth to support interpretation of surface seismic data (Hardage 1985). VSP applications are now quite diverse; for example, VSP techniques have been used as imaging tools in areas where access for surface seismic surveys is restricted (Gras and Craven, 1997) or to map fault zones in the hardrock environment (Cosma and Heikkinen, 1996). Since 1990, several seismic reflection studies have taken place in the zinc-producing Matagami mining camp of northwestern Quebec. The first seismic experiment (Adam et al., 1998) demonstrated that seismic methods could effectively map the deep volcanic stratigraphy. Based on these results, the Geological Survey of Canada and Noranda Inc. decided to investigate the use of seismic reflection methods to directly locate deep massive sulphide bodies. The occurrence of Bell Allard, a 6 Mt deposit

at a depth of 1 km, provided an ideal target to test seismic methods as a tool for deep exploration. Petrophysical laboratory measurements of common sulphides by Salisbury et al. (1996) demonstrated their characteristically high acoustic impedance. Similar measurements in the Matagami mining camp confirmed that the Bell Allard deposit would cause a seismic reflection (Adam et al., 1996). The acquisition of a 2D seismic profile directly above the Bell Allard deposit (Calvert et al., 1999) revealed a high-amplitude anomaly believed to originate from the sulphides. Due to the complex geology (faulting, moderate dip, mafic intrusions) which may generate out-of-plane reflections, a VSP survey was chosen to confirm the orebody reflectivity. The VSP technique has the unique advantage of providing a direct link between geological features intersected by a borehole and seismic data. One VSP was acquired in a borehole that penetrated the eastern part of the orebody (BAS-94-33f) whereas the other was about 200 m away from the ore zone (BAS-92-25). In the Matagami mining camp, most ore deposits are associated with an exhalite horizon called the Key Tuffite. The initial objective of the survey was to compare the reflectivity between the mineralized and the barren Key Tuffite. This objective was never met because borehole BAS-92-25 was blocked above the Key Tuffite.

This paper presents an overview of the orebody geology and aspects of the data acquisition and processing. A first order interpretation of the VSP data reveals the velocity structure of the volcanic rocks found at Matagami. The processed VSP section, together with numerical modelling of the ore deposit, confirmed its high reflectivity and provided some insight about the use of VSP surveys as a mineral exploration tool.

4.2.3 Geological Setting

Bell Allard is a typical Matagami camp VMS deposit. It is located at the Key Tuffite, horizon marking the Watson Lake (rhyolite and rhyodacite) - Wabasee (basalt and andesite) groups interface, atop a synvolcanic fracture zone. The deposit is bounded to the south by a syn-volcanic fault system (Boundary Fault) oriented 95° relative to north. The orebody consists of two lenses and is approximately 370 m long and 165 m wide down dip

along the Key Tuffite interface with an overall east-west orientation in plan. The north lens is composed primarily of high-grade Zn-rich massive sulphides (sphalerite) and the southern lens is of lower grade and is comprised, in part, of alteration zone type mineralization. Sulphide mineralization consists of pyrite, Fe-rich sphalerite, minor chalcopyrite and pyrrhotite. The thickness averages about 30 m, but can range up to 60 m in portions of the south lens. The deposit dips 50° to 55° towards the south between depths of 900 and 1150 m below the surface. A total resource in excess of 6 Mt makes Bell Allard the second largest deposit discovered in the Matagami mining camp.

4.2.4 Data acquisition

The VSP shotholes were located in an area of thick (~ 40 m) overburden. The source consisted of 227 g pentolite boosters pushed about 0.3 m into the clays at the bottom of water-filled pits. This provided good source coupling. The downhole receiver unit consisted of three orthogonal 14 Hz geophones and a wall locking device attached to a 1200 m long, seven conductor, steel armoured cable. Three geophone groups were placed in the vicinity of the borehole collar and data collected at these locations were used to correct for shot statics. The sampling rate was set at 0.1 ms and the record length was 0.5 s for BAS-94-33f and 0.6 s for BAS-92-25.

The collar locations and surface projections for boreholes BAS-94-33f and BAS-92-25 in relation to the orebody are shown in plan view in Figure 4.1a and on an east-west section in Figure 4.1b. The shothole locations used for the VSP surveys are also shown in Figure 4.1a. In borehole BAS-94-33f, a total of 154 recordings were made at various receiver intervals to a depth of 1075 m. A receiver spacing of 10 m was used for the upper 808 m, 5 m in the 808 to 908 m depth range, and 2.5 m from 908 m to 1075 m depth. In borehole BAS-92-25, the receiver spacing was 10 m between 113 and 465 m and 5 m from 465 m to 850 m. A blockage at 850 m prevented data collection at the Key Tuffite level (1021 m).

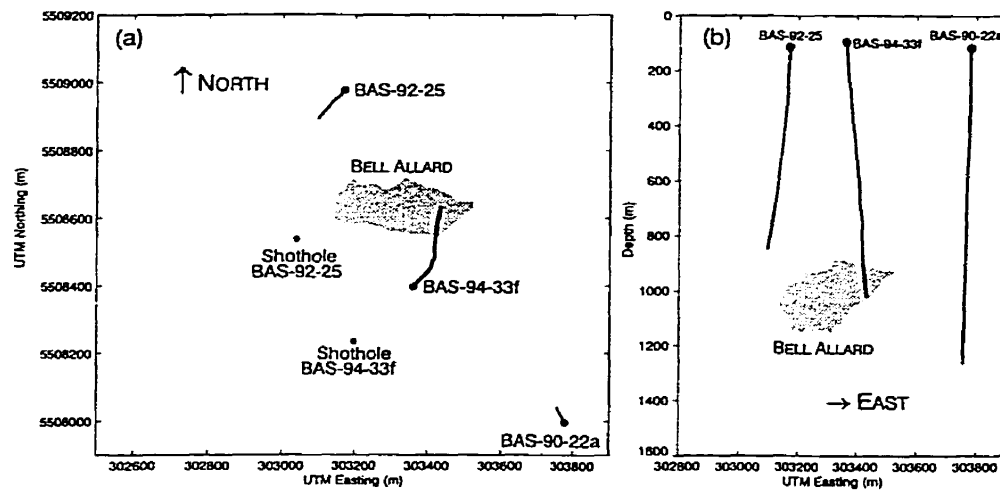


Figure 4.1: a) Location map showing the borehole in which the VSP data were acquired or used in the modelling study. The outline of the Bell Allard deposit is indicated. b) East-west section showing the depth of Bell Allard and the borehole locations.

4.2.5 Data processing

The most striking feature of the Matagami VSP data, when compared to similar surveys done in sedimentary basins, is the low amplitude of the reflections. This is largely due to the small reflection coefficients between the lithological contacts. For these reasons, great care must be taken during data processing to preserve the weak upgoing wavefield. Some of the processing challenges that were encountered included the elimination of strong electrical noise and removal of the dominant downgoing energy. Traces recorded at the bottom of the borehole were particularly affected by 60 Hz and its harmonics (up to 660 Hz) from high-voltage powerlines and a nearby transformer station. The noise level was so high that the first breaks could not be identified on the raw seismic records. Such noise cannot be effectively removed with a conventional notch filter because of its high amplitude and the low FFT resolution (2 Hz) that result in leakage over a large frequency band (~ 20 Hz). To prevent the loss of such a wide frequency bands, less destructive alternative approaches were applied to the VSP data (Nyman and Gaiser, 1983). The bandwidth of the signal was determined through the application of different bandpass filters and the optimum seismic

image was obtained by using frequencies between 30 and 180 Hz. Some of the filtered traces showed minor delays on the surface geophones and the borehole receivers that are caused by shot timing. To correct for the shot delays, first breaks recorded at the surface geophones were used to estimate the shot statics, which were then applied to the downhole data. Strong downgoing P- and S-waves, which partly mask upcoming events, were suppressed using a median filter (Hardage, 1985). F-k filters have also been tested but were not as effective as a median filter in removing the downgoing waves. After subtraction of the downgoing waves the upcoming wavefield is revealed and reflections are clearly identified (Figures 4.4a and 4.5a). A 30-180 Hz bandpass filter and only trace energy balancing based on the amplitude of the direct P- and S-wave arrival have been applied prior to their removal. Hence, reflections amplitude are relative to the direct wave amplitudes.

4.2.6 Interpretation

The data collected at Bell Allard were first analyzed to obtain a P- and S-wave velocity model. Processed data from borehole BAS-94-33f confirm the strong reflectivity of massive sulphides whereas the final processed VSP section from BAS-92-25 shows a weak reflection from a basalt-rhyolite contact.

4.2.6.1 Seismic wave velocities

Velocity information is important for the data processing and calibration of surface seismic data. In particular, velocities derived from a VSP experiment are most useful since they use the same source types as in surface seismic surveys. When plotted against source-receiver distance, P- and S-wave first break times show a linear relation (Figure 4.2). The linear regression of the first break times yielded a P-wave velocity of ~ 6300 m/s and a S-wave velocity of ~ 3600 m/s. For borehole BAS-94-33f, the static shift caused by the thick overburden was estimated at 21 ms from the P-wave data and the S-wave data. This value is in good agreement with the refraction static solution obtained from the analysis of the 3D surface seismic data in the shot location area. The good fit between the linear regression

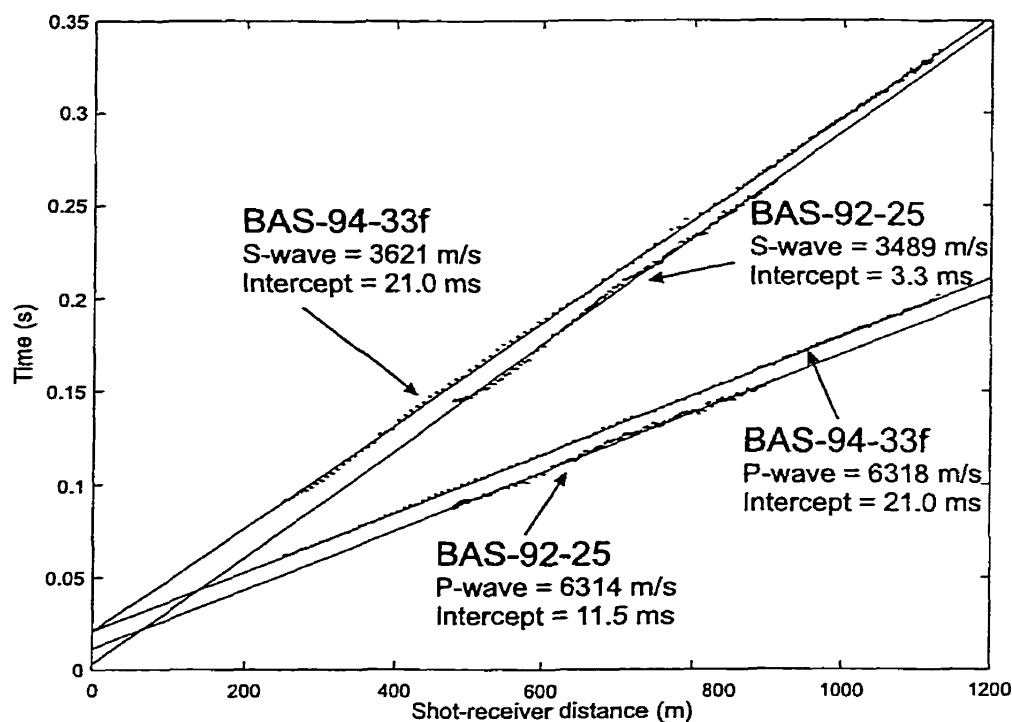


Figure 4.2: VSP P- and S-waves first break analyses. The solid line is the linear regression results computed from the first break pick values (dots).

results (solid lines on Figure 4.2) and the first break data (dots on Figure 4.2) shows that velocities are approximately constant in the upper 1 km of the crust.

Full waveform sonic data were collected in borehole BAS-94-33f between 47 and 1000 m wireline depth using a 0.1 m spacing. To compare the full waveform sonic logging velocities and the VSP data, the VSP velocities have been derived from linear regressions of the first break times using a 21 points sliding window. The sonic velocities (grey line) are plotted together with the VSP velocities (black line) on Figure 4.3. While the two velocity estimates are in agreement for the top 500 m, there is a larger discrepancy at greater depth. Such discrepancies were anticipated given the large source-borehole collar offset (~200 m) and the 45° stratigraphic dip in the survey area. The full waveform sonic logs typically measure the velocity of a region of about 1 m around the borehole (Ellis, 1987), whereas the velocities derived from an offset VSP survey represent velocity changes between the shot and receiver location along a different travelpath. Nonetheless, a linear regression performed

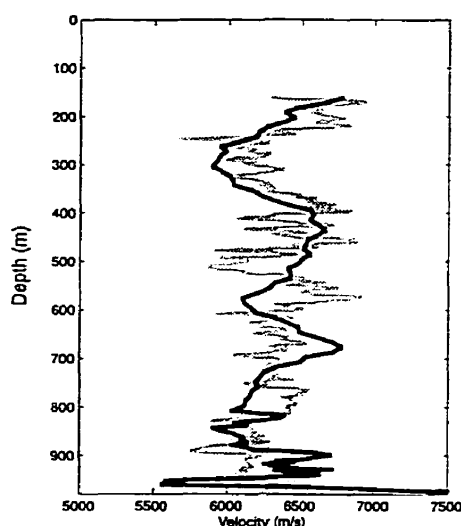


Figure 4.3: Comparison between the VSP (solid line) and full waveform sonic velocities (grey line) in borehole BAS-94-33f.

on the sonic cumulative travelttime curve produced a velocity only 0.3% higher (6310 m/s) than the average VSP velocity, thus confirming the accuracy of the two independent in situ velocity measurements. This good agreement between the VSP and the sonic average velocities in the two boreholes suggests that the lateral and vertical velocity variations within the Wabasse Group are relatively small.

4.2.6.2 Modelling the scattering response from Bell Allard

To understand better the seismic response from the Bell Allard orebody, a simple numerical model was built from a set of geological cross-sections through the deposit. The surface of the orebody was interpolated onto a regular 5 m grid. It was assumed that the scatterer is embedded in a homogeneous crust with a P-wave velocity of 6300 m/s, an S-wave velocity of 3600 m/s (corresponding to the average velocities of the direct waves, Figure 4.2), and a density of 2700 kg/m³. The Bell Allard deposit was modelled as homogeneous sphalerite with a P-wave velocity of 5500 m/s, an S-wave velocity of 2750 m/s, and a density of 4300 kg/m³.

Synthetic surveys using the same geometries as realized in the field experiments were

simulated using two different modelling programs: the very fast program BMOD3D (Eaton, 1997), which is based on the Born approximation (Eaton, 1999), and the accurate but computationally expensive 3D Finite Difference (FD) method (Bohlen et al., this volume). For efficiency, we used BMOD3D to compute the P-wave scattering response for the evaluation of different acquisition geometries where a high number of shot-receiver configurations were simulated. The FD method was applied for a direct comparison of the synthetic and measured scattering response in the nearfield (BAS-94-33f) and farfield (BAS-92-25). The source wavelet used in the FD computations has a dominant frequency of approximately 50 Hz, and was derived by averaging the wavelets of the direct P-waves.

4.2.6.3 Borehole BAS-94-33f

The direct comparison of the vertical components recorded in BAS-94-33f (Figure 4.4a) with the corresponding 3D FD seismograms (Figure 4.4b) allows the reliable identification of the strong events which were measured directly above the Bell Allard orebody (Figure 4.4a). The first event is a Backward scattered P-wave (marked by PP in Figure 4.4a,b) which has an apparent velocity of about 6300 m/s corresponding to the crystalline background velocity. The second event is a converted S-wave (indicated by PS in Figure 4.4a,b) propagating with an apparent velocity of ~ 3600 m/s, i.e. the background S-velocity. The converted S-wave is mainly polarized horizontally. Figure 4.4c shows that the synthetic amplitudes decrease abruptly in the nearfield of the ore (from 950 to 1000 m depths) and then decrease proportional to $1/\text{distance}$, which is due to the geometrical spreading of the scattered wavefield.

4.2.6.4 Borehole BAS-92-25

The final processed section (Figure 4.5a) shows one weak reflection that projects to a depth of about 900 m (RB on Figure 4.5a). This reflection correlates with a 40 m thick rhyolite horizon in contact with basalts; rhyolite-basalt contacts are known to be reflective in this mining camp (Adam et al. 1998). The FD synthetic response from Bell Allard is

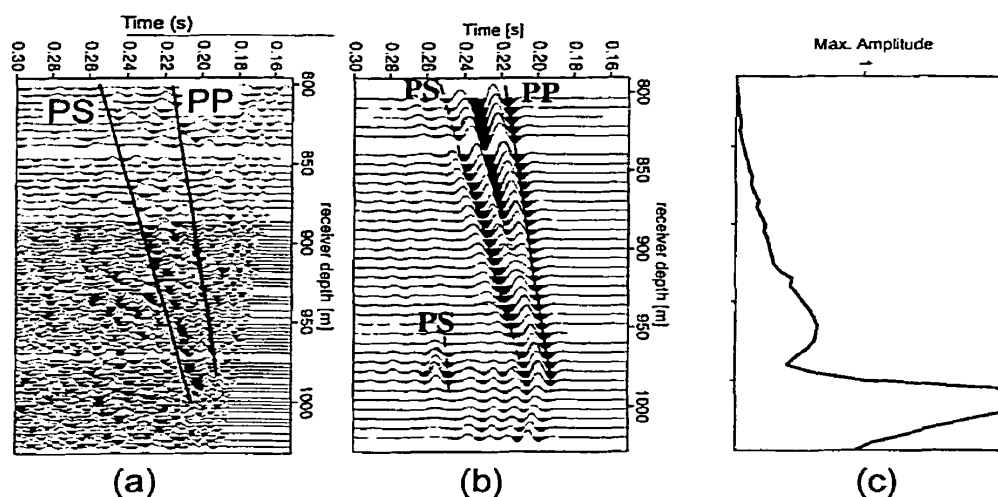


Figure 4.4: Final processed VSP section from borehole BAS-94-33f b) Trace normalized FD seismograms of Bell Allard. c) Trace maximum absolute amplitude values of b). The scattered PP and PS waves can be identified clearly in the measured seismograms. High amplitudes are expected in the nearfield of the ore deposit while they are much smaller and rapidly decaying above the ore zone.

displayed in Figure 4.5b. Obviously the scattering response from Bell Allard could not be detected in this borehole. The maximum absolute amplitudes of the synthetic response (Figure 4.5c) are much weaker (~ 50 times) than those encountered in BAS-94-33f which is partly due to geometrical spreading effects. In addition, shape and composition effects may significantly decrease the scattering response for that azimuth. Therefore it appears unlikely that a response from the deposit could be recorded, given the weak amplitudes of the synthetic response. Bohlen et al. (this volume) and Eaton (1999) have shown that a dipping lens scatters energy in a preferred direction (downdip). Consequently, the response from a dipping lens would be stronger if the receivers were positioned in the downdip direction instead of updip as is the case for the VSP in BAS-92-25. Other VSP geometries with other azimuthal coverages may favor imaging of massive sulphides. For future surveys, regional dip and strike of an orebody need to be considered in a detailed modelling study.

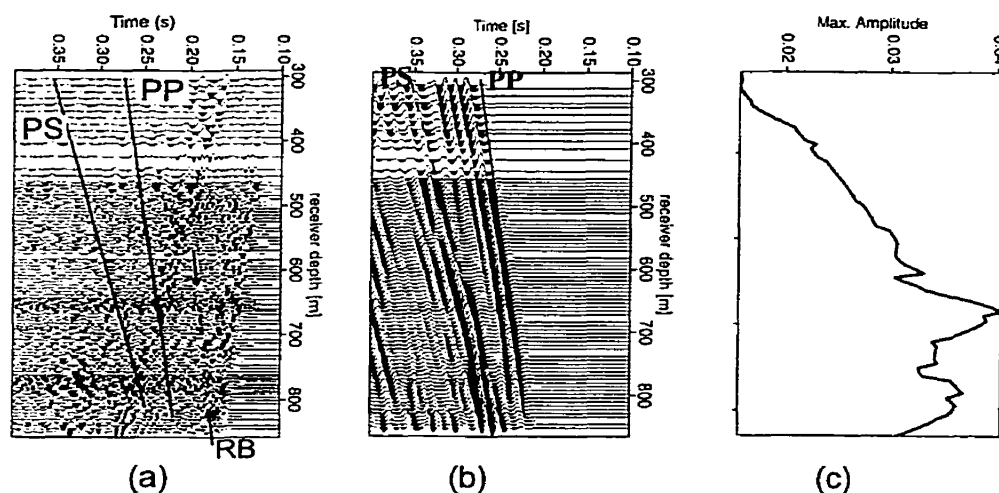


Figure 4.5: a) Final processed VSP section from borehole BAS-92-25 b) FD synthetic seismograms normalized on maximum amplitudes c) Trace maximum absolute amplitude values of b). Due to geometrical spreading amplitudes 200 m away from the ore are much weaker than those observed directly at the ore in BAS-94-33f.

4.2.7 Optimizing the shot position

In the previous sections, the modelling and field results from two VSP acquired in the vicinity of the Bell Allard deposit have been shown. Since one VSP recorded a scattering response from Bell Allard, we have an indication of the lower detection limit of a VSP survey. Clearly, the amplitudes recorded in borehole BAS-94-33f were strong enough to allow the detection of the orebody while those recorded in borehole BAS-92-25 were too low. The good agreement between the field data and the synthetic seismic section (compare Figure 4.4a and 4.4b) confirms that the numerical model, even if simplistic, is sufficient to explain the recorded wavefield in the vicinity of Bell Allard.

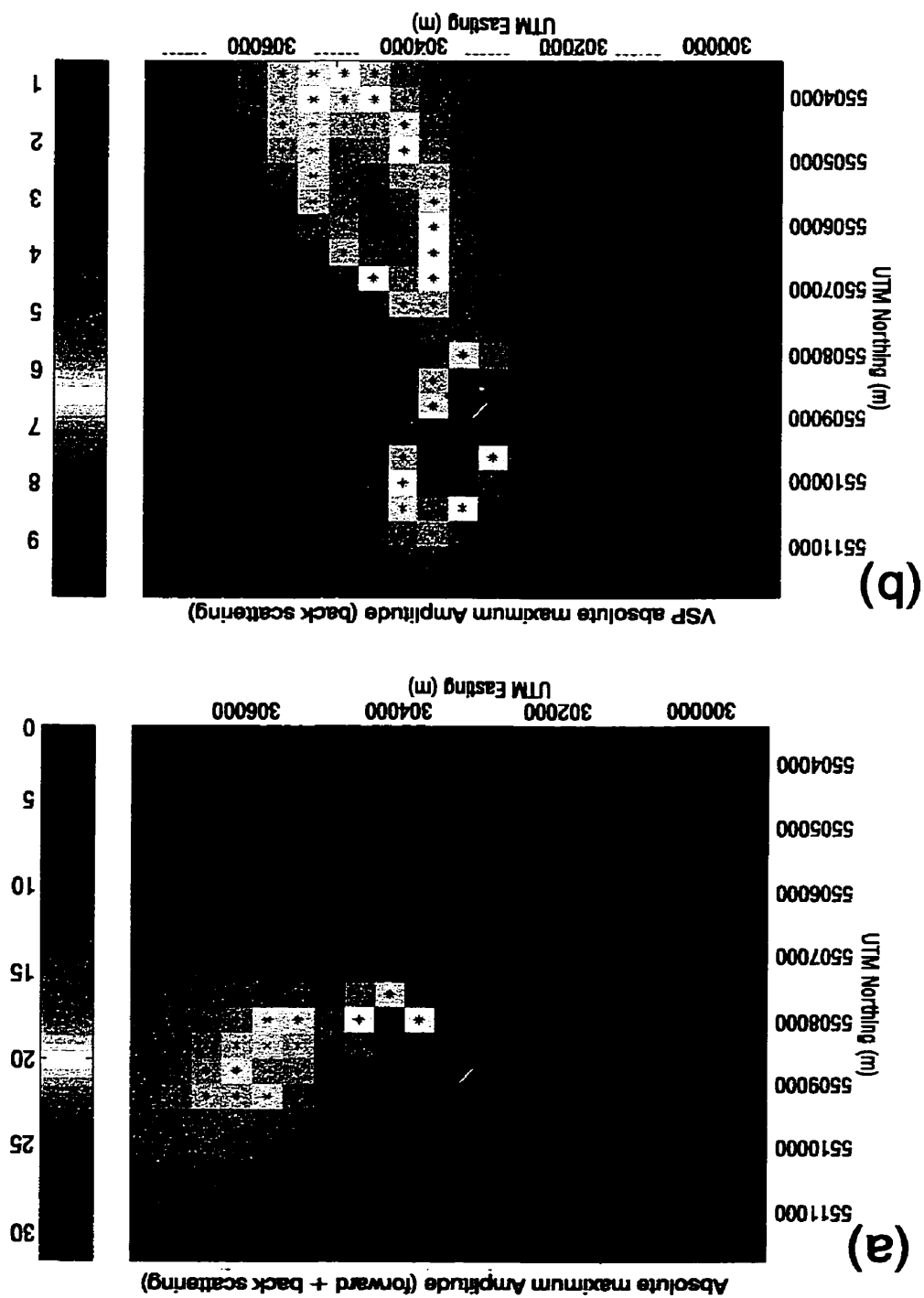
The absence of a response from Bell Allard in the VSP from hole BAS-92-25, raised the question about the optimum shot location to illuminate the ore deposit: if the source was placed at a different location, would Bell Allard be detected in that borehole? To better understand the seismic response from Bell Allard, several VSP geometries have been simulated. A total of 441 shots on an 8 km² grid have been modelled using BMOD3D (Eaton, 1997). The synthetic seismic responses contain only the P-wave reflections from

Bell Allard without direct P- and S-waves. A receiver spacing of 10 m has been used. Actual borehole geometries and locations have been used in the simulations to facilitate follow-up VSP studies and calibration of the modelling results.

Since the ability of VSP techniques in detecting a scatterer depends strongly on the amplitudes of the seismic response, VSP modelling results are summarized by their maximum absolute amplitudes. Figure 4.6 shows the survey geometry in plan view and the modelling results in terms of the maximum absolute amplitudes of the full VSP sections as a function of the shot position (stars on Figure 4.6a) as recorded by the receivers (white line on Figure 4.6a) placed along borehole BAS-92-25. Figure 4.6a shows that the highest amplitudes are expected from a shot placed about 1 km to the southeast of the orebody. Figure 4.7b shows the synthetic VSP section modelled using a shot point located in this region. The strongest amplitudes expected at depths below Bell Allard are downgoing (forward) scattered P-waves. These events are asymptotic to the direct P-wave arrivals and it may be difficult to distinguish the two wave types on actual VSP sections. Furthermore, downgoing waves can be recorded only at depths below the target and their identification requires a borehole deeper than the target. On the other hand, the seismic energy scattered towards the surface (upgoing) dips in the opposite direction of the direct P-wave arrivals and thus the two events can easily be identified. Performing the same analysis as presented in Figure 4.6a, but with upgoing reflections, reveals that the shot location that maximizes the seismic energy is different (Figure 4.6b). The optimum shot location, which maximizes the upgoing seismic energy, is about 500 m north of Bell Allard. Whereas the offset between the source and the target is significantly reduced ($\sim 50\%$), the amplitudes of the waves scattered upwards are 60% less than those scattered downwards. For comparison, the modelling results using the actual shot location are shown in Figure 4.7c. Whereas the amplitudes are slightly weaker than those predicted from the shot location that maximizes the amplitudes of upgoing P-waves (Figure 4.7a), they are significantly lower than the maximum amplitudes of the downgoing waves (Figure 4.7b).

This study shows that the shot location used to acquire the VSP data in borehole BAS-

Figure 4.6: a) Maximum absolute amplitudes of each synthetic VSP surveys simulated for borehole BAS-92-25. Clearly, the strongest amplitudes are recorded for a shot location down-dip from the orebody (south). The receiver locations are indicated by the white line, the orebody in red, and the shot point locations are marked with a star. b) Maximum absolute amplitudes of the upgoing P-waves at each synthetic VSP surveys simulated for borehole BAS-92-25.



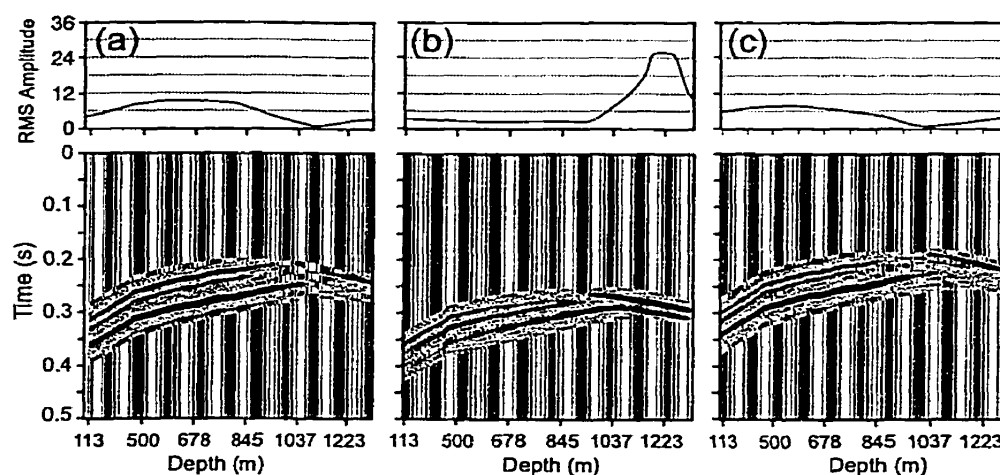


Figure 4.7: a) Synthetic response of a VSP in borehole BAS-92-25 with a shot located at 303300E, 5509200N where the maximum absolute amplitude of the upgoing reflection from Bell Allard is maximized. b) Synthetic response of a VSP with a shot located at 304100E, 5508000N where the maximum absolute amplitude of the downgoing reflection from Bell Allard is maximized. c) Synthetic response of the actual VSP survey (shot at 303045E, 5508523N).

92-25 was not optimal for imaging of the Bell Allard deposit. It also shows that upgoing reflections, if they were strong enough, should have been recorded by receivers located in the top 900 m of the borehole; yet no events have been identified in the actual dataset. While strong downgoing scattered P-waves could have been generated using a shot placed 1 km to the southeast of Bell Allard, the proximity of the event to the downgoing P-wave may have prevented its identification. This hypothesis cannot be easily verified because this borehole is blocked at a depth of 850 m.

4.2.7.1 VSP technology as a mineral exploration tool

Reflection seismic methods are generally well suited for deep mineral exploration because of their high resolution and depth penetration compared to standard electromagnetic methods. Currently, in the Abitibi Belt, the mineral exploration industry relies heavily on borehole electromagnetic (BHEM) methods (Boivin and Lambert, 1997) to locate orebodies within a 150 m distance around the borehole. As the exploration depth increases, the cost of boreholes also increases. Enlarging the radius of detection of ore deposits around

a borehole could reduce the exploration budget and the time required locating new ore reserve. Due to the usually low attenuation of seismic waves in the hardrock environment, VSP technology potentially has a larger radius of detection than conventional BHEM if the target has a sufficient acoustic impedance contrast. To determine the detection radius, a modelling study similar to the one performed in borehole BAS-92-25 has been undertaken using borehole BAS-90-22a located 700 m to the southeast of Bell Allard (Figure 4.1). If a VSP survey acquired in this borehole could locate an orebody such as Bell Allard, it could become a valuable exploration tool. The receivers used in the modelling study were placed at 10 m interval between 100 and 1250 m wireline depths. Figure 4.8a shows the maximum absolute amplitudes of the synthetic modelling results for the same shot location used in Figures 4.6a and 4.6b generated using the same numerical model for Bell Allard. Figure 4.8b shows the maximum absolute amplitudes of the upgoing reflections from Bell Allard. With this geometry, the optimum shot position is about 3 km from Bell Allard and from the borehole collar (Figure 4.8). It is also interesting to note that even if the borehole is 700 m from Bell Allard, the maximum absolute amplitude is expected to be 50% larger than those obtained from the optimum geometry using borehole BAS-92-25 that is only 200 m from the orebody.

These results suggest that in the case of an orebody like Bell Allard, optimal shot point location may need to be placed as far as 3 km from the target (for a survey in borehole BAS-90-22a) to maximize the amplitude of the seismic response. Complex-shaped orebodies like Bell Allard cause strong variations of the scattered amplitudes with offset and azimuth. Thus, the optimum shot location varies as a function of the receiver location and it is difficult to predict this location without using a forward-modelling tool.

4.2.8 Discussion

The modelling results from a small number of boreholes indicate that, to assess the necessary (important) azimuthal range of scattering angles in the VSP measurements of Bell Allard, source-target distances as high as 3 km are required. Using large and optimal

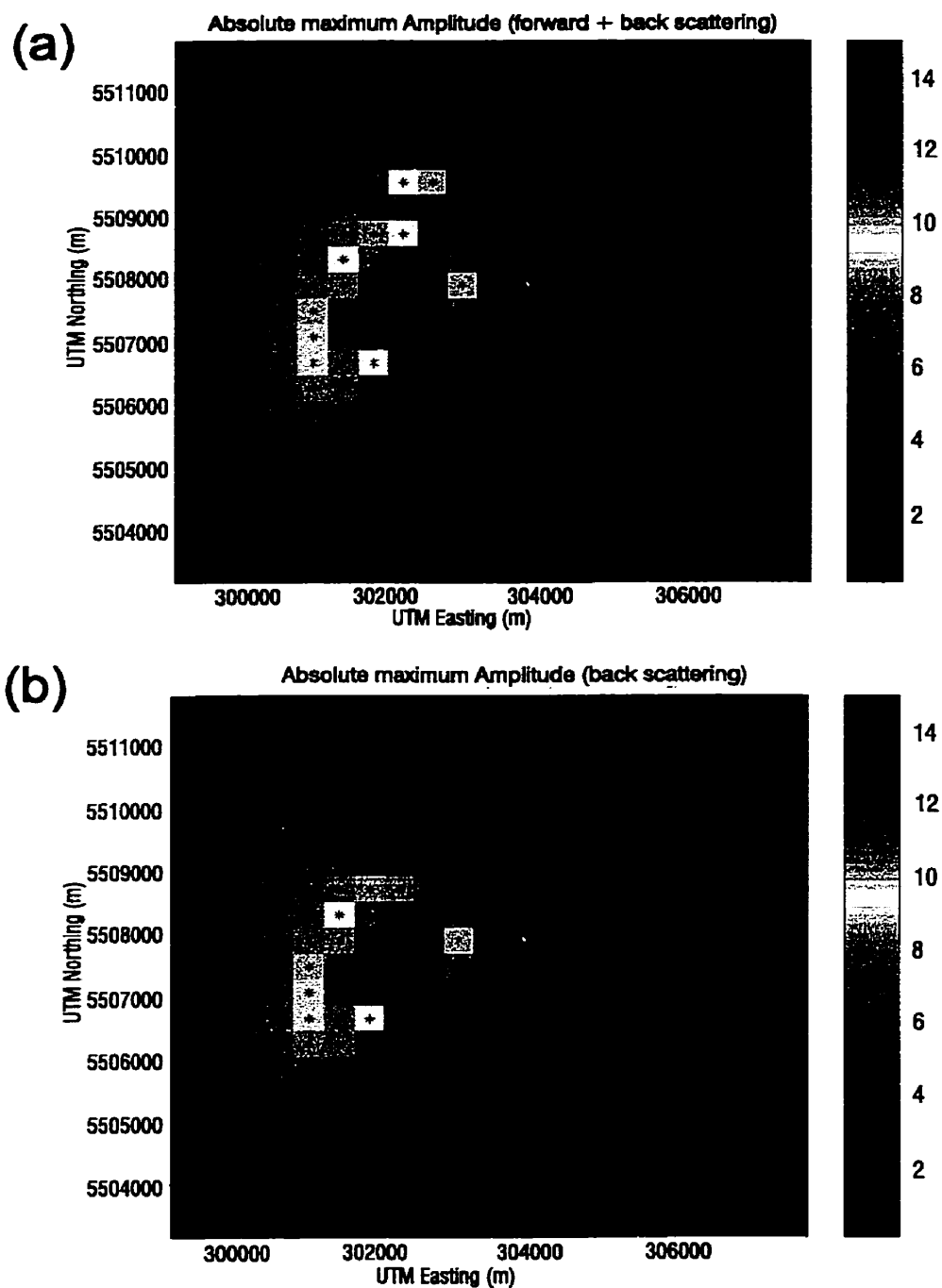


Figure 4.8: a) Maximum absolute amplitudes of upgoing and downgoing scattered P-waves recorded in borehole BAS-90-22a. The receiver locations are indicated by the white line, the orebody in red, and the shot point locations are marked with a star. b) same as a) but for only the upgoing scattered P-waves.

source-receiver separations would facilitate data processing by enhancing the signal to noise ratio: the direct wave would have reduced amplitudes whereas the orebody response would be enhanced. In this case, removal of the direct waves is simplified. One encouraging result from our modelling study, using borehole BAS-90-22a located 700 m away from Bell Allard, is that a stronger upgoing scattered P-wave (Figure 4.9c) may be generated than the one expected from borehole BAS-92-25 (Figure 4.9b). However, upgoing P-waves are much weaker than those modelled using BAS-94-33f (Figure 4.9a). Note that in areas where massive sulfides have higher acoustic impedance, the overall seismic reflection amplitudes will be increased. However, the directional variability of the scattered energy may be stronger (Bohlen et al., this volume). If reasonable assumptions regarding the dip, strike and depth of the target can be made, then a simple modelling study, such as presented here, can help to determine the optimum shot location. In other cases, where no a priori information is available, the VSP survey may require a grid of shotpoints which would make the VSP survey logistically complicated as well as more costly. In this case, a full 3D survey could be more cost effective.

4.2.9 Conclusions

The linear regressions performed on the P- and S-wave first break times for holes BAS-94-33f and BAS-92-25 indicate that, in the upper 1 km of the crust, the P-wave velocity is ~ 6300 m/s while S-wave velocity is estimated at ~ 3600 m/s. The average seismic velocity estimated from the VSP data is comparable to the velocity derived from the full waveform sonic logging data. The VSP data collected in hole BAS-94-33f confirm that the Bell Allard deposit has a strong seismic response with clear P-wave and converted S-wave reflections. Whereas the main objective of the study, to test the reflectivity of mineralized versus barren rock, has not been met because one of the boreholes was blocked, these two VSP surveys provide important insights into the seismic signature of a sphalerite-rich VMS deposit. The strong amplitude of the scattered P-wave energy observed in borehole BAS-94-33f is attributed to the large impedance contrast between the orebody and the surrounding

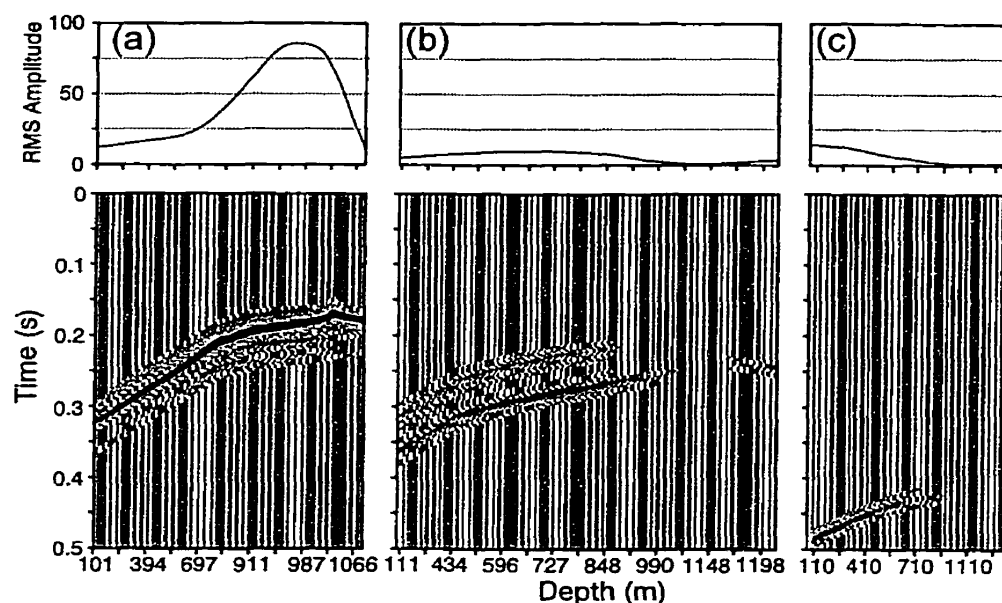


Figure 4.9: Comparison of the synthetic amplitudes between the response obtained in borehole BAS-94-33f (a) with the response using the VSP configuration that maximizes the amplitudes of the upgoing reflection from Bell Allard recorded by borehole BAS-92-25 (b) and BAS-90-22a (c). Due to geometrical spreading the expected amplitudes from BAS-92-25 and BAS-90-22a are much weaker than those from BAS-94-33f.

volcanic rocks. Lithological contacts within the volcanic sequence are less reflective than the ore/host rocks contacts, as shown by the weak reflection recorded in borehole BAS-92-25.

The modelling study using borehole BAS-92-25 has shown that, even if the shot location used to acquire the VSP data was not optimal, the upgoing P-wave amplitudes are not expected to be much higher with an optimum shot point. Hence, the detection of Bell Allard with receivers placed in borehole BAS-92-25 can be achieved only if the raw data quality is improved or if the deeper portion of the borehole were accessible to allow the recording of the strong downgoing scattering response. In the Matagami area, the use of VSP technology as an exploration tool is limited because only weak upgoing reflections are expected from the Bell Allard deposit. Furthermore, large shot-target offsets are required and the optimum shot location depends largely on the target geometry and location. Given that the Bell Allard deposit is not concordant with the regional dip and strike, the optimum

shot location for testing the presence of other deposit cannot be identified. Nonetheless, this study shows that complete modelling study must be an integral part of survey design if this method is to be used as an exploration tool.

4.2.10 Acknowledgments

This research was partly funded through an Industrial Partnership Program between the Geological Survey of Canada (GSC) and Noranda Inc. Full waveform sonic logging was performed by the Mineral Resources Division of the GSC. Acquisition of the VSP in borehole BAS-92-25 was funded through an NSERC operating grant awarded to Andy Calvert. The authors thank Noranda Inc. for their permission to publish results from this research project. The finite difference modelling was performed on the CRAY SV1 supercomputer of Kiel University. This is GSC contribution XXXXX.

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CHAPITRE 5

3D SEISMIC IMAGING FOR VMS DEPOSIT EXPLORATION, MATAGAMI, QUEBEC

5.1 Introduction

L'article "3D seismic imaging for VMS deposit exploration, Matagami, Quebec" constitue le quatrième chapitre. Il a été soumis en février 2000 pour publication dans le livre "Hardrock seismic exploration methods" édité par B. Milkereit, D. Eaton, et M. Salisbury. Cet article présente les résultats du levé 3D qui a imagé le gisement Bell Allard et défini la limite sud-ouest du camp minier. Cette étude montre que la sismique est un outil efficace pour explorer la partie profonde des camps miniers.

L'exploration pour les gisements profonds dans les camps miniers existant est cher et prend beaucoup de temps. La sismique réflexion 3D est utilisée régulièrement en exploration pétrolière pour cartographier les contacts stratigraphiques et les structures géologiques. L'application de cette méthode à la cartographie des unités volcaniques et à la détection du dépôt SMV Bell Allard situé à 1 km de profondeur a été récemment vérifiée dans le camp minier de Matagami. Les objectifs du levé étaient d'identifier la réponse sismique du gisement de Bell Allard et de cartographier les principaux contacts lithologiques. La signature sismique du gisement de Bell Allard se présente comme une zone de fortes amplitudes sismiques d'une largeur de 100 m. Le gisement est situé au-dessus d'une anomalie d'ampli-

tude plus grande qui est interprétée comme un sill de gabbro ou la cheminée d'altération du dépôt. L'étude montre aussi que la profondeur de la principale cible d'exploration (la Tuffite Clé) peut être déterminée sur une grande partie du levé sismique et que la limite sud-ouest de l'interprétation définit la position d'une faille importante (faille Daniel). D'autre part, l'orientation et le pendage d'une faille synvolcanique ont été déterminés à partir de l'analyse d'amplitude d'une intrusion de gabbro. Le levé sismique 3D de Matagami démontre que cette technique peut identifier les dépôts SMV profonds et les contacts lithologiques à l'échelle régionale. Le coût d'un levé 3D est comparable à celui de deux trous de forage d'une profondeur de 800 m par km². Lorsque appliquée dans un environnement géologique favorable, la sismique 3D a le potentiel d'assister l'exploration minérale à grande profondeur et d'accroître les chances de faire des nouvelles découvertes tout en réduisant les coûts d'exploration.

5.2 Article 4

3D seismic imaging for VMS deposit exploration, Matagami, Quebec

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5.2.1 Abstract

Detecting deep mineral resources in the vicinity of existing mining camps is expensive and time consuming. The 3D seismic method is used routinely in oil and gas exploration to map deep stratigraphic contacts and structural features. Its ability to map volcanic contacts and the 1 km deep Beli Allard volcanogenic massive sulphide (VMS) deposit was tested recently in the Matagami mining camp. The survey objectives were to identify the seismic response of a VMS ore deposit and to map the main lithological contacts. The Bell Allard VMS deposit appears as a 100 m wide zone of high seismic amplitudes. The deposit is underlain by a larger amplitude anomaly that we attribute to a gabbro sill, or possibly to the alteration zone of the deposit. We show that the depth of the main exploration target (the Key Tuffite) can be interpreted on a large portion of the seismic survey area and that its southwest limit defines the location of a regional fault (the Daniel fault). The azimuth and dip of a synvolcanic fault was determined from amplitude analysis of a large gabbro sill. The Matagami 3D seismic experiment shows that seismic methods can image a deep VMS deposit and map important lithological contacts at a regional scale at a cost comparable to two 800 m deep boreholes per square kilometre. When applied in the appropriate geological context, a 3D seismic survey has the potential to assist deep mineral exploration and increase the chances of making cost-effective discoveries.

5.2.2 Introduction

The 3D seismic reflection experiment in the Matagami district of northern Quebec represents the culmination of a 10-year research project lead by the Geological Survey of Canada, with support from three major Canadian mining companies and several universities. The experience gained by conducting seismic surveys in several mining camps and in various geological settings resulted in a preferred strategy to implement seismic methods in the mineral exploration context. The favoured approach consists of 3 distinct phases. The objective of the first phase is to estimate the acoustic impedance (the product of density and velocity) of the target and its host rocks by in-situ methods and laboratory measurements on rock

samples. Reflection amplitudes are directly related to the acoustic impedance contrast at lithological contacts. A minimum contrast of 10% with the background acoustic impedance appears necessary to reflect the seismic waves with sufficient intensity to be observed at the surface. In the second phase, the estimated target reflectivity is verified by acquiring a vertical seismic profile (VSP). In a VSP experiment, a shot is placed at surface and the seismic wavefield is recorded at regular depth intervals in a borehole. Reflections observed using this survey geometry can be directly correlated with geological features intersected by the borehole. If the target reflectivity is confirmed, a seismic line is acquired in the third phase to ensure that the target can be mapped from the surface, to estimate its continuity, and to determine the optimum acquisition parameters (such as frequency content, fold, charge size, etc.). Only after the successful completion of the 3 preliminary phases is a 3D survey planned using the acquisition parameters determined from the 2-D seismic survey. The 3D seismic survey has the capability of mapping complex geological structures in their correct position. High-probability drill targets can then be established.

Why explore for deep mineral deposits in the Matagami mining camp? The Matagami mining camp is an important Canadian zinc producer (Canada is the world leader in production of this metal (Statistics from Natural Resources Canada, 1996)). The zinc-rich ore deposits of the Matagami mining camp are typical of the primitive Archean volcanogenic massive sulphide (VMS) type (Franklin et al., 1981). Whereas only 22% of the total world production of zinc comes from VMS deposits, in Canada it accounts for 48.6% (Singer 1995). Thus, exploration for Canadian VMS deposits is important for the Canadian economy and to maintain world zinc supplies. In particular, the Matagami mining camp is a major producer with 6.7% of the Canadian zinc production in 1997 (Industrie Minière du Québec, 1997). Also, because VMS deposits are polymetallic, their exploitation is often less affected by the fluctuations in the price of any individual metal (Riverin, 1999). However, they are generally small in tonnage (median size is 1.25 Mt) and therefore, for the majority of VMS deposits to be economic, they must be located in the vicinity of larger deposits (Riverin, 1999). Since the initial discovery at Matagami (Matagami Lake mine) in 1963, exploration

has progressed from surface to depths exceeding 1000 m. Until now, the mineral industry has relied heavily on deep drilling to test prospective stratigraphy because conventional surface geophysical methods (e.g. EM, magnetic surveys) are generally limited to the upper few hundred meters. Given the small size of the deposits and the high exploration cost for deep massive sulphide deposits, alternate methods of prospecting favourable horizons are being sought. The Seismic Technology Research Project initiated by the Geological Survey of Canada and Noranda Inc. began in 1990 in response to this need and, in part, because of the opportunity provided by the Lithoprobe multi-disciplinary study of the Abitibi subprovince of the Canadian Superior Province.

Two high-resolution seismic profiles across the South Flank of the Matagami volcanic complex were acquired in 1990 and 1993 and have shown that surface seismic methods could effectively map the moderately dipping ($< 45^\circ$) South Flank stratigraphy (Adam et al., 1998; Calvert et al., 1999). These initial surveys have been followed by a number of complementary studies: 1) to define physical rock properties (in situ and laboratory measurements) (Cinq-Mars et al., 1995; Salisbury et al., 1996); 2) to compute the theoretical 3D seismic responses (Adam et al., 1996); and 3) to establish optimal seismic acquisition parameters. A decision was then made to carry out a 20 km² 3D seismic reflection survey to cover an area of the South Flank overlying the newly discovered Bell Allard deposit. The primary survey objectives were: 1) to use Bell Allard as a benchmark; 2) to locate other deposits with similar seismic signatures within the survey area; and 3) to provide operational models for costing future surveys. Here we detail the processing and interpretation of the 3D seismic survey in Matagami and the implications for VMS exploration in this camp and in similar geological settings.

5.2.3 Geological Setting

The Matagami volcanic complex is located in the eastern part of the Harricana-Turgeon belt of northern Abitibi subprovince (Lacroix et al., 1990) and was formed by two major phases of predominantly tholeiitic volcanism. The early phase produced dacites and rhyo-

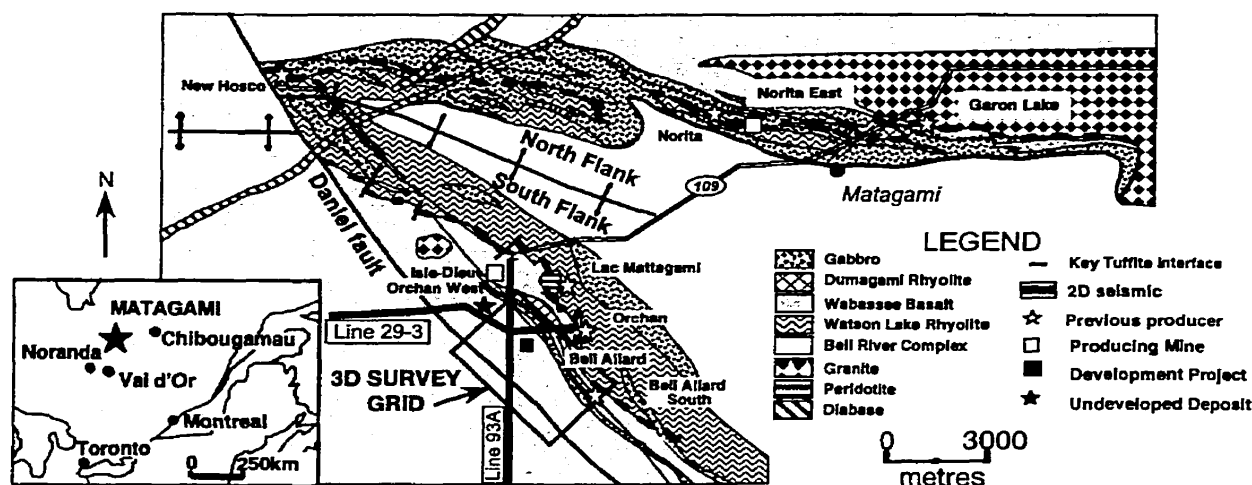


Figure 5.1: Geology and mineral deposits of the Matagami camp showing the location of the 2D seismic profiles and the 3D seismic survey area.

lites of the Watson Lake Group (Figure 5.1), whereas the younger phase, which produced the Wabasseé Group, was dominated by basaltic volcanism with subordinate felsic activity and was accompanied by mafic-dominated sub-concordant intrusions (Piché et al., 1993; Beaudry and Gaucher, 1986). A cherty, sulphidic chemical sediment known as the Key Tuffite marks the contact and hiatus between the two formations and is traceable for many kilometres along strike and down-dip on the South Flank of the mining camp (Sharpe, 1968). This thin horizon (0.6-6 m) was deposited during a period of intense hydrothermal circulation and represents the primary exploration target in the camp because it is host to most of the orebodies discovered to date (Piché et al., 1993). The Matagami volcanic complex is bounded to the south by immature volcanic-derived clastic sediments and iron-formation of the Taibi Group across an important structural discontinuity, and to the north by the Matagami Group sediments composed mainly of siltstone and argillite with subordinate granitoid-pebble conglomerate (Beaudry and Gaucher, 1986).

The volcanic and sedimentary rocks were intruded during several episodes. The Bell River complex, which underlies and intrudes the Watson Lake Group, is a tholeiitic complex consisting of a layered sequence of gabbro with stratiform magmatic oxide concentrations, capped by a felsic granophyric unit (Maier et al., 1996; Beaudry and Gaucher, 1986). This

intrusion is thought to be syn-volcanic in age and may have been the heat source for the hydrothermal activity observed within the overlying volcanic succession (Maier et al., 1996; MacGeehan, 1978; Sharpe, 1968).

The volcanic rocks of the Matagami complex are folded into an open, gently north-west plunging structure known as the Galinée anticline (Sharpe, 1968). Rocks on the south limb of the anticline, where the study area is located, are weakly deformed and metamorphosed, and dip approximately 45° to the southwest (Piché et al., 1993). The north limb stratigraphy is subvertical and has been segmented into a number of distinct lozenge-shaped domains separated by zones of coalescing deformation (Piché et al., 1993). On the south limb, the Daniel reverse fault, a family of northwest-trending, moderately to steeply north-east dipping structures, has thrust the south limb stratigraphy and Bell River Complex over the Wabasee Group volcanics (Piché et al., 1993). Estimates of vertical displacement across the structure are variable, but range to more than 1 km (unpublished Noranda internal reports).

5.2.3.1 General deposit geology

Bell Allard is a typical Matagami camp south-flank VMS deposit. It is located at the Watson Lake-Wabasee groups interface atop a synvolcanic fracture zone characterized by classic hydrothermal alteration. A weakly transposed concordant lens of sulphide mineralization directly overlies a discordant pipe, or conduit, hosting massive to stringer mineralization (Figure 5.2). The deposit is bounded to the south by a syn-volcanic fault system (Boundary Fault) oriented 095° relative to north. The orebody consists of two lenses and is approximately 370 m long and 165 m wide down dip along the Key Tuffite interface, with an overall east-west orientation in plan. The north lens is composed primarily of high-grade Zn-rich massive sulphides whereas the southern lens is of lower grade and comprised, in part, of conduit-type mineralization. Sulphide mineralization consists of pyrite, Fe-rich sphalerite, minor chalcopyrite and pyrrhotite. Thicknesses average about 30 m, but can range up to 60 m in portions of the south lens. The deposit dips 50 to 55° towards the

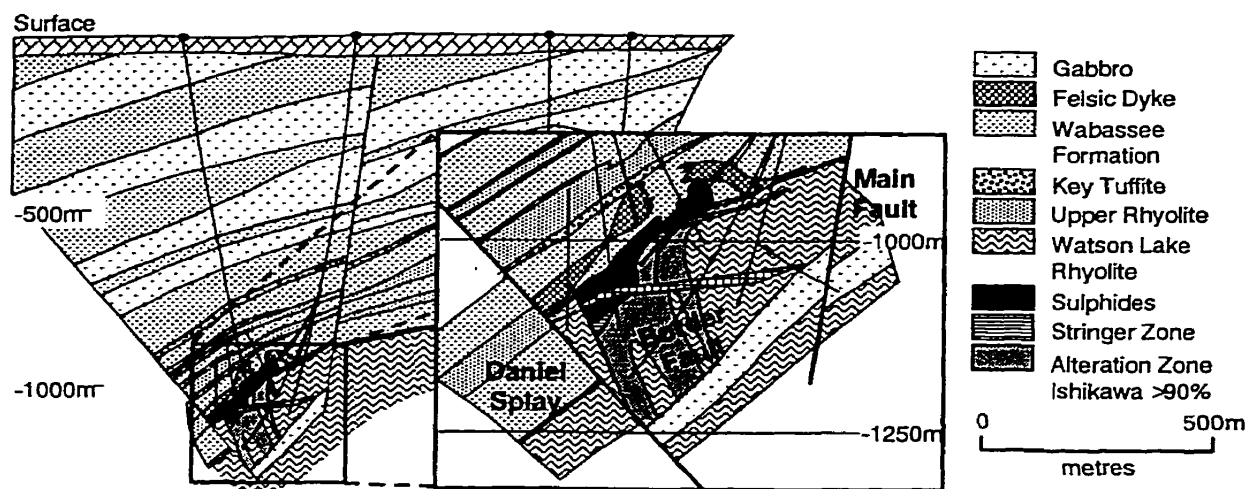


Figure 5.2: Vertical section through the Bell Allard deposit.

south between depths of 900 and 1150 m below the surface. A global resource in excess of 6 Mt makes Bell Allard the second largest deposit discovered in the Matagami mining camp. The 1994 production decision was based on a drill-indicated reserve of 3.2 Mt grading 13.77% Zn, 1.50% Cu, 43.45 g/t Ag and 0.76 g/t Au (unpublished Noranda internal reports).

5.2.4 Physical rock properties

Physical rock properties of the main lithological units are summarized in Figure 5.3, where ellipses are centered on the median density and P-wave velocity values for a particular host rock type. Salisbury et al. (1996) suggest that some sulphides commonly associated with VMS deposits (e.g. pyrite) have high acoustic impedances. *In-situ* and laboratory measurements were conducted to verify if these findings were applicable to the sulphides of the Matagami mining camp. P-wave velocities were obtained from full waveform sonic logging data collected through 100 m of massive sulphides (borehole 94-26a). Laboratory density measurements were performed on split core samples. Laboratory density and P-wave velocity measurements were determined for 7 core samples of massive and disseminated sulphides and 3 samples from a neighboring mine (Isle-Dieu). Reflection amplitudes are

proportional to the reflection coefficient. For example, rhyolite in contact with a gabbro or a sulphide/magnetite rich lens generate the strongest reflections. Figure 5.3 clearly shows that P-wave velocities and densities of the Bell Allard orebody contrast with those of the surrounding volcanic units. The highest impedance values are found for pyrite-rich samples (6, 20a, and 20b on Figure 5.3) whereas most of the volcanic rocks (95%) have impedances below $22 \cdot 10^6 \text{ kg/m}^2\text{s}$. This contrast suggests that a strong acoustic impedance contrast exists at the contact between Bell Allard and its host rocks. Pyrite and magnetite have the highest acoustic impedances values; hence, these two non-economic minerals probably control the reflectivity of Bell Allard. Whereas size and shape also affect the reflection amplitude, the existence of a significant acoustic impedance contrast at the target is absolutely necessary.

5.2.5 Seismic data acquisition

The seismic crew was in Matagami between April 13 and April 23, 1996; only 10 days were needed to layout the receivers, acquire the seismic data, and remove the equipment. A total of 956 shots were recorded with a 2048 channel capacity seismograph in less than 36 hours (between April 17 and 19). A state-of-the-art, 24-bit acquisition system was used due to the anticipated relatively low signal-to-noise (S/N) ratio compared to those typical of the oil and gas environment. Significant efforts were made to achieve good shot and receiver coupling: 1) shot charges were placed as close as possible to the overburden-bedrock interface (15 m average depth) to maximize seismic energy penetration and minimize source generated noise; 2) at each receiver station, about 1 to 1.5 m of snow had to be removed to allow the placement of geophones directly on the ground surface. The survey took place during spring thaw and temperatures were below the freezing point at night but well above freezing during the day; thus, the geophones were frozen into the ground in the morning, providing excellent receiver coupling. In general, the topography of the 3D grid is gentle with bogs in some areas and a dense spruce forest and clear-cut in others. The maximum elevation on the grid is 296.8 m above sea level with a maximum elevation difference of only

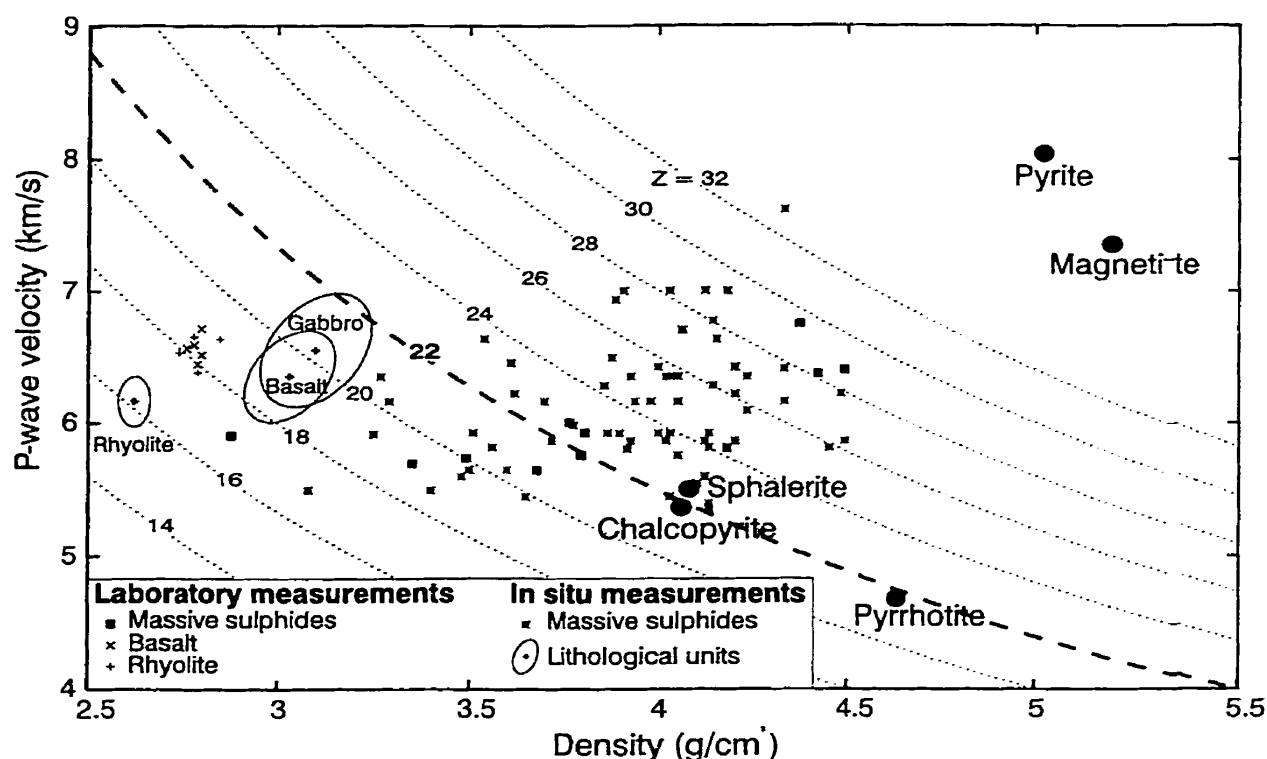


Figure 5.3: P-wave velocities and densities from logging hole 94-33f, and massive sulphides intersected in hole 94-26a. Laboratory data from core and samples from Bell Allard and Isle-Dieu orebodies (squares). Most volcanic units have acoustic impedances of less than $22 \times 10^6 \text{ kg/m}^2\text{s}$ (heavy dashed line) while sulphides have acoustic impedances above $22 \times 10^6 \text{ kg/m}^2\text{s}$. Ellipses around lithologic units show 1 standard deviation of their sample distribution. Densities and P-wave velocities for common minerals found in VMS deposits are shown for reference by the large dots (Salisbury et al. 1996). Iso-impedance contour lines (in units of $10^6 \text{ kg/m}^2\text{s}$) are overlain to help estimate reflection coefficients between rock units.

40 m.

In total, 20 km^2 ($4 \times 5 \text{ km}$) of 3D seismic data were acquired above and around the Bell Allard deposit (see Figure 5.1). The seismic grid was positioned to favor a good illumination of the Key Tuffite, to record the seismic response of Bell Allard, and to identify other possible drill targets to the south-east of Bell Allard. The dynamite shots (0.34 kg of pentolite) were recorded by up to 1900 receivers located along 19 receiver lines. The 50 m shot spacing and 40 m receiver spacing used for this survey yielded a 25 by 20 m subsurface bin size. The shot and receiver line spacing controls the fold and the offset distribution in each

Table 5.1: Data acquisition parameters.

Source Information	
Energy source	0.34 Kg of Pentolite at 15 m average depth
Source interval	50 m
Source line spacing	400 m
Receiver Information	
Geophone type	10 Hz MARK PRODUCTS UM-2-A
Geophone interval	40 m
Geophone layout	6 in a 1 m linear array
Receiver line spacing	250 m
Acquisition System	
Instrumentation	GEO-X Aram 24
Pre-Amp Gain	36 dB
Field filter	164 Hz High-cut
Record length	3 s
Sample rate	2 ms

common mid-point location. Using a large number of receivers increases the fold and the shot receiver offset. Recordings at large source-receiver offsets are particularly important in complex geological settings or where the velocity gradient is weak or absent. The acquisition parameters are summarized in Table 5.1.

Analysis of the raw shot gathers in the field revealed the good data quality even in the presence of high-levels of source generated and cultural noises (Figure 5.4). Clear reflections were observed on the raw shot gathers. The amplitude spectrum of a shot gather of average quality (station 14125 - Figure 5.4b) clearly indicates that frequencies as high as 160 Hz were recorded, and also shows the dominance of a high-amplitude, low-frequency ($< 30\text{Hz}$) component mostly associated with the source generated noise (ground roll and S-waves). Four major sources of ambient noise were identified on the seismic grid during data acquisition: 1) drilling, blasting, and mucking in the Bell Allard shaft, 2) traffic along Highway 109 (Figure 5.1), 3) electrical noise around a high-voltage substation and powerlines located within the survey area, and 4) mining activities at neighboring installations (Isle Dieu mine and concentrator at Mattagami Lake mine). The production shaft, excavated to extract the ore from the Bell Allard deposit, was in progress at a depth of 60 m by

mid-April 1996. Mining activities associated with the Bell Allard shaft were intermittent: sometimes unnoticed (e.g. while cementing) and sometimes affecting about 100 receiver stations around the shaft when drilling. Receiver line 29 was located very close to the shaft and on some occasions more than 50 receivers along this line were affected by shaft sinking activities. As an example, receiver line 29 of shot 8109 (Figure 5.4c) was contaminated by different kinds of cultural noise (mucking? and electrical noise). After the application of a 30 Hz high-pass and adaptive filters (Figure 5.4d), most of the coherent noise has been removed from the shot gather. Traffic along Highway 109 was intermittent and only affected a few traces at a time; it did not necessitate trace editing. A high-voltage powerline and substation are within the 3D seismic grid and electrical noise (60, 120 and 180 Hz) affected receiver groups that were located close to these installations, but was removed with an adaptive filter (Adam and Langlois, 1996) (Figure 5.4d). A nearby mine (~ 2 km from the survey grid) and the concentrator located about 1 km away from the survey area did not stop production during the seismic experiment. To help compensate for the high-cultural noise level, a large number of receiver stations were employed. A minimum of 1700 receivers was deemed necessary.

5.2.6 3D seismic data processing

It is now widely accepted that data acquired in the hardrock environment poses different challenges than for data collected in a sedimentary environment (Milkereit and Eaton, 1998), largely because of the high velocities and relatively low reflectivities encountered in crystalline rocks. The thick low-velocity overburden that is in contact with unweathered high-velocity basement rock is responsible for large static corrections, severe high-frequency attenuation, and multiple wave conversions. Imaging the high-velocity basement itself with a resolution comparable to a survey for oil and gas exploration requires the use of high frequencies (> 100 Hz). Crystalline rocks are also generally characterized by a smoothly varying and low-amplitude velocity gradient; hence, seismic raypaths are almost straight. Consequently, to image steeply dipping structures properly, recordings at large source-receiver

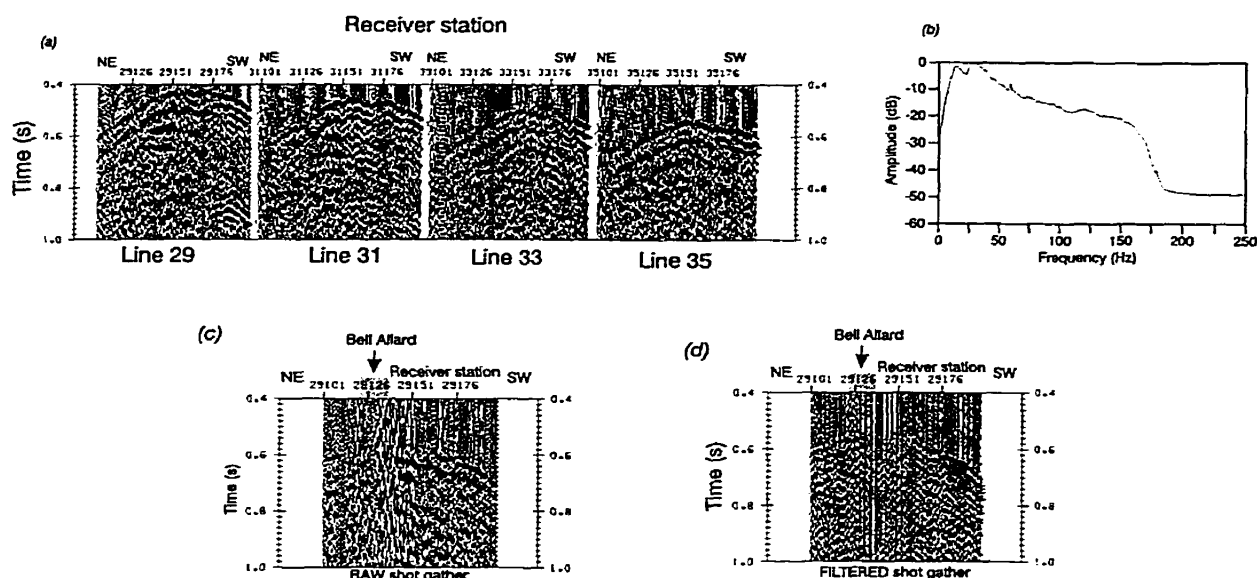


Figure 5.4: (a) Receiver line 29,31,33 and 35 from shot 14 125. The Bell Allard orebody is located directly beneath Receiver line 29. (b) Amplitude Spectrum of traces shown in (a). (c) Receiver line 29 of shot 8109 is affected by different kind of cultural noise (Electrical noise and mucking). (d) Same as (c) after applying a 30Hz high-pass filter and removing the 60Hz noise with an adaptive filter.

offsets are necessary. Another complication is caused by the generally low reflection coefficients ($< 10\%$) compared to those encountered in sedimentary basins. To compensate for the lower reflectivity, high-fold and high-fidelity recording systems must be used. Nonetheless, some data processing steps are simplified in the hardrock environment. Because the velocity field does not vary significantly, detailed velocity analysis is not as important as it would be for processing of data from sedimentary strata of an oil and gas prospect. The application of imaging algorithms (DMO and migration) is also greatly simplified. Whereas the different velocity fields between crystalline and sedimentary rocks has a direct impact on data acquisition, it has an even more profound impact on the data processing. *Ignoring these fundamental differences when designing seismic surveys and during processing data can only lead to failure.* In processing seismic data from the crystalline crust, the most important step is the evaluation of accurate weathering static corrections, whereas detailed velocity analysis and residual static corrections generally provide minor improvements. As is the case for data acquired in any structurally complex sedimentary setting, the focusing

steps (DMO, migrations) are crucial to image the dipping lithological contacts.

Data processing of the 3D dataset has benefited from the experience of processing 2D seismic data in the area since 1990 (Milkereit et al., 1992; Adam et al., 1998; Calvert and Li 1999). The processing flow (Table 5.2) used for the 3D seismic is very similar to the one applied to the 2D data. The exception is the lack of cross-dip corrections, a key processing step for a crooked 2D line, but not required here.

The unmigrated stack is used to identify the scattering response from local high acoustic impedance bodies (e.g. ore deposits, faulted gabbro intrusions). The circular anomalies observed on timeslices that are associated with this type of targets are most distinctive on the unmigrated stack, whereas reflections from other targets are unfocused and do not appear at their true position. On the migrated stack, circular anomalies (diffractions) are collapsed to a small area located at the apex of the diffraction hyperbola and the anomalies are smaller in size than on the unmigrated stack. On the other hand, the migrated stack provides the best 3D image of lithological contacts and faults at their true subsurface location. In the following section, emphasis is on the static correction problem and imaging of dipping contacts. Inline 161 was chosen to illustrate the effect of these most important processing steps because it exhibits shallow, deep, dipping and sub-horizontal reflectivities.

5.2.6.1 Refraction static corrections

The computation of an accurate refraction weathering static solution is by far the most important processing step. Processing of 2D seismic data from the Matagami area (Adam et al., 1998; Calvert and Li, 1999) has shown that static corrections obtained from the generalized linear inverse method (Hampson and Russell, 1984) improved signal continuity and the signal-to-noise ratio. The refraction static correction computed with this method resulted in accurate long and short wavelength solutions. About 35500 (4.7% of total) first break picks were automatically rejected by the software after the first iteration because the times were inaccurate. Overburden velocities were extracted from uphole times and the overburden velocities derived from these values resulted in a better static solution than when

Table 5.2: Processing sequence

Electrical noise removal	Adaptive time domain filter
Geometry	25 x 20 m subsurface bins
Trace editing	Bad shots are excluded
True amplitude recovery	$A = A * t$
Spiking deconvolution	Minimum phase, 100 ms window, 1% noise
Bandpass	Ormsby minimum phase 10-20-130-150 Hz
Gain	AGC 3000 ms
First break mute	Linear ramp between 30 and 50 ms below first breaks
Refraction statics*	
- First break picks	Automatic (neural network algorithm)
- Datum	300 m Above Sea Level
- Correction	GLI3D (Hampson-Russell)
Surface consistent residual static corrections	Method: maximum stack power maximum shift: 10 ms window: 0.1- 1.2 s

Unmigrated Stack

DMO corrections	
Stacking velocity analysis	Constant-velocity stacks
NMO corrections	6100 m/s 50% stretch allowed
Scaling	500 ms (AGC)
Stack	
Bandpass	Butterworth 25(40 dB slope)-80 Hz (20 dB slope)

Migrated Stack

Prestack migration	Equivalent offset, full aperture, 20 m bin size, maximum offset 10 km
Stacking velocity analysis	Semblance and constant-velocity stacks
Scaling	500 ms (AGC)
Stack	
Bandpass	Butterworth 25(40 dB slope)-80 Hz (20 dB slope)

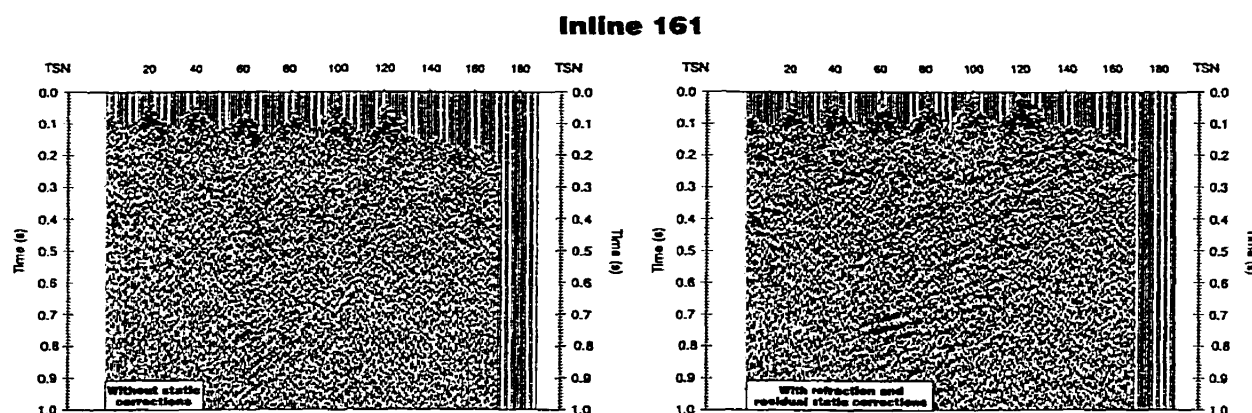


Figure 5.5: a) Inline 161 without refraction static corrections applied. B) Inline 161 with GLI3D refraction static corrections applied.

a constant velocity was used. After 5 inversions and short-wavelength static calculations, the average error was 3.55 ms which is quite acceptable considering that the sample rate is 2 ms. The maximum total refraction static was 88 ms in the northern portion of the grid where there is a thick layer of dry sand. Comparatively, the maximum elevation correction was only 14 ms, more than 6 times smaller. Figure 5.5 shows the effect of applying refraction static corrections on the stacked section of inline 161. Without static corrections, the section exhibits little reflectivity and the only noticeable reflection is at 0.75 s below crossline 60. After applying refraction static corrections, reflections become visible at depth (between 0.7 and 0.8 s on Figure 5.5b), as do weak reflections from 0.2 s.

5.2.6.2 Imaging

In areas where lithological contacts are dipping, the imaging step (i.e. dip moveout (DMO), migration) is crucial to obtain enhanced reflections from these contacts (compare Figure 5.5b and 5.6a). For these two sections, the processing flow and stacking velocity are the same, apart from the DMO corrections. When the seismic data is stacked using the correct interval velocity, the resulting seismic sections emphasize the reflectivity from sub-horizontal geological structures (Figure 5.5b). Higher stacking velocities are necessary to allow dipping reflections to stack correctly. DMO corrections allow both dipping and

sub-horizontal events to stack using the background interval velocity (Figure 5.6a). After correcting for DMO, reflections are imaged more clearly, but they are not at their true subsurface location. Hence, DMO is a partial migration process that produces a zero offset section. A migration can later be applied on the DMO stack to collapse diffraction hyperbolas and move reflections to their true subsurface position. In theory, for a constant background velocity, DMO followed by poststack migration should produce the same results as a prestack migration. Important differences in the final migrated stacks (Figures 5.6b and 5.6c) are probably due to the implementation of each algorithm: the commercial DMO implementation (Figure 5.6b) used gave little control on the choice of parameters (e.g. operator aperture, bin size, offset range), whereas the in-house implementation of the prestack migration (Figure 5.6c) allowed much more flexibility. The key difference between the unmigrated and migrated sections is the appearance of diffraction hyperbolas and the detection of point scatterers (e.g. orebodies).

The diffraction from a dipping lens has two characteristic features: 1) an amplitude anomaly down-dip and 2) a phase reversal that depends on the lens shape and composition. Detecting this complex diffraction response is a processing challenge. A full prestack migration effectively collapses the diffracted energy, but these characteristic variations of amplitude with azimuth are lost. Also, because of the phase reversal, migrating the data reduces the anomalous amplitudes due to destructive interference. Therefore, partial prestack migration techniques, such as DMO, are best suited to preserve the diffraction hyperbola generated by an orebody. From the exploration point of view, the zero-offset stacked section is more appropriate for detecting massive sulphide deposits: 1) the diffraction pattern is larger, 2) the amplitudes are stronger, and 3) the amplitude versus azimuth anomaly can give some information about the lens geometry.

Whereas full prestack migration might not help in the direct detection of ore deposits it will image structures and stratigraphy that define the host geological environment. The prestack migration by equivalent offset (Bancroft, 1996) was applied on a 10 km² subset of the 3D survey that includes the Bell Allard deposit. Whereas the DMO seismic section

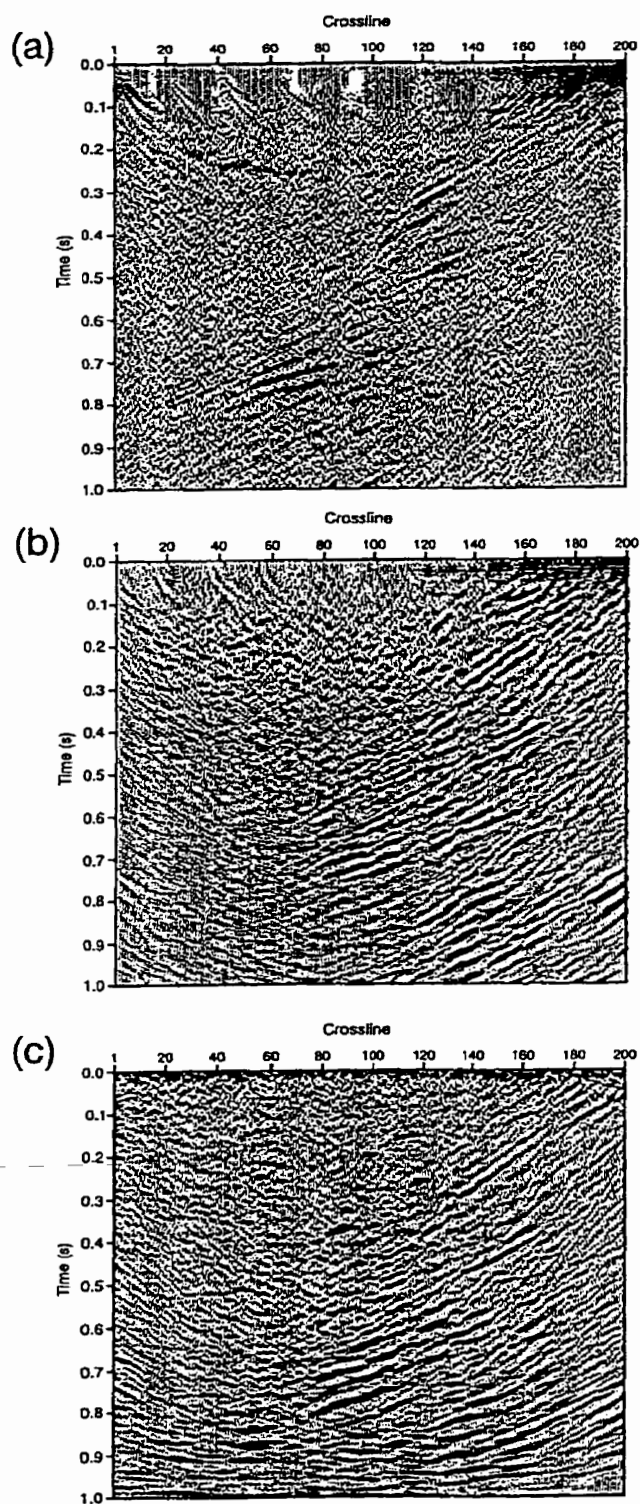


Figure 5.6: a) Inline 161 with dip-moveout corrections. b) Same as a) but with a poststack phaseshift migration followed by a FX deconvolution c) Inline 161 after equivalent offset prestack migration.

(Figure 5.6b) has ample reflectivity in the area of interest (0.2 - 0.4 s), the reflection character is homogeneous and horizons are difficult to follow across the section. In such a heavily faulted area, this stacked volume is quite difficult to interpret. The prestack migrated version of inline 161 (Figure 5.6c) is superior to the poststack migrated section; it has more detail and reflections can be correlated across the section. From this improved section, several faults can be inferred by locating small offsets along the main reflections. These results demonstrate that full prestack migration can be a valuable processing tool, with the potential to greatly improve and facilitate stratigraphic and structural data interpretation in crystalline rocks.

5.2.7 Interpretation

5.2.7.1 Reflections from regional-scale lithological contacts

Within the seismic data volume, some continuous reflections (e.g. gabbros and upper rhyolite) have been imaged laterally for several kilometres. Mapping these horizons was straightforward and could even be automated. Other important contacts and structures, such as the Key Tuffite and the Daniel fault, could not be directly associated with a reflection and required more detailed interpretation in order to identify them. Locating the depth and lateral extent of the Key Tuffite was an important objective of the 3D seismic project. In particular, the Daniel fault intersects the Key Tuffite at about 1.4 km with the sequence deepening significantly to the west of the fault. The location of where the Daniel fault intersects the Key Tuffite is a key element when planning a deep exploration program. During the interpretation process, the borehole information was used to validate the interpretation, to identify reflective contacts, and to refine the accuracy of the interpretation.

Gabbro sills

The petrophysical measurements in several boreholes located in and around the 3D seismic survey area have shown that rhyolite-gabbro contacts produce the strongest reflections. In particular, tholeiitic magnetite-rich gabbros found in the area are more reflective because

magnetite has a high velocity and density. Gabbro sills in the Watson Lake Group, which is dominated by low impedance ($\sim 16 \cdot 10^6$ kg/m²s) rhyolite and rhyodacite (Figure 5.3), provide prime candidate contacts, if sharp, to generate strong reflections. The potentially high acoustic impedance contrast where gabbro intrudes felsic volcanic rocks, makes the reflection seismic method an ideal tool to map this type of contact at the regional scale. Within the seismic survey area, a thick (~ 100 m) gabbro sill sub-parallel to the Key Tuffite is known to intrude the Watson Lake Group from borehole information. This sill is distinct from the Bell River complex, ~ 1 km deeper in the section. To define the extent of this sill a filter has been applied to the final seismic image: the average root-mean-square (RMS) amplitude was calculated from the prestack migrated volume using a 100 ms sliding window. Whereas this type of display has a lower vertical resolution, it has the advantage of integrating data from successive timeslices and reduces the effect of local amplitude anomalies. The result of this filter on a timeslice at 396 ms (~ 1200 m), the depth level around which the tabular gabbro sill is located, is shown on Figure 5.7. Since the filter has a length of 100 ms, the amplitudes shown on Figure 5.7 represent data between 1050 and 1350 m. In this case, the well-defined lateral extent of the gabbro sill is indicated by the dark areas on Figure 5.7 that correspond with a zone of strong reflections. A striking feature of the RMS amplitude timeslice is a linear zone of low reflectivity (arrows on Figure 5.7) in the northern part of the gabbro sill. The orientation of this low reflectivity zone is not obvious on a conventional wiggle trace display. This zone appears to correspond with the Main fault mapped in the vicinity of Bell Allard (Figure 5.2) that may be a reactivated synvolcanic feature associated with the emplacement of the ore deposit. If the reflectivity reduction was caused by a fault zone, it has several implications: 1) the fault was active after the gabbro was emplaced, 2) the fault zone is about 80 m wide and, 3) the fault is subvertical (because of the 300 m amplitude averaging). The importance of gabbro sills in locating fault zones has been recognized by Calvert and Li (1999). In the case of a 3D survey, the location and azimuth of near vertical faults can be derived from the analysis of averaged RMS seismic amplitudes around conveniently located large gabbro sills. Given the

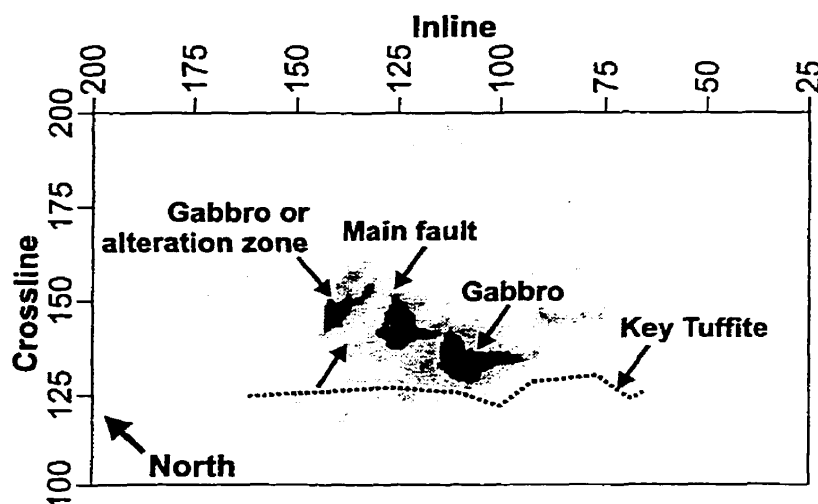


Figure 5.7: Amplitude map of a timeslice at 400 ms (~ 1200 m). The location of the interpreted Key Tuffite is indicated by the dotted line. High amplitudes (dark areas) are associated with a gabbro intrusion that underlies the Key Tuffite over a large area.

large number of synvolcanic gabbro sills in most of the Abitibi mining camps, this type of analysis is a tool to help in the identification of synvolcanic faults that can focus the search for VMS mineral deposits.

Key Tuffite

The most important regional contact is the Key Tuffite because most ore deposits found in the mining camps are located at this interface. Knowing the depth and lateral extent of this horizon is important to establish mineral exploration programs in the mining camp. However, finding the Key Tuffite on seismic data is a difficult task because it is too thin to generate a reflection. Interpretation of seismic profiles (Milkereit et al., 1992; Adam et al., 1998) revealed that reflective thick rhyolite horizons interlayered with basalt and gabbros at the base of the Wabasse Group, could be used to map the Key Tuffite indirectly. On the Lithoprobe profile 29-3 (Adam et al., 1998), the Watson Lake group was transparent, thus the Key Tuffite could easily be found because it was located at the contact between a highly reflective sequence (the Lower Wabasse Group) and the generally transparent

Watson Lake Group. The seismic characteristics of the Watson Lake Group, in the area covered by the 3D seismic survey vary: in some areas it is seismically transparent while in others it is intruded by gabbro that generate strong reflections. Also, the reflectivity of the base of the Wabasse Group depends on the thickness of the rhyolite horizons that varies at the regional scale. In some boreholes, rhyolite thickness within the Wabasse Group exceeds 100 m, whereas in other regions (in particular in the southeast) it is less than 30 m. Consequently, it is not possible to locate the Key Tuffite based only on a simple reflectivity change. The strong reflectivity within the Lower Wabasse Group is localized and thus it cannot be used to locate the Key Tuffite at the mining camp scale.

Gabbro sills are reflective in the Watson Lake Group where they are juxtaposed with rhyolites and rhyodacites; however these gabbros are poor reflectors in the basalt-dominated Wabasse Group. Hence, the seismic response of a gabbro sill cutting through the Key Tuffite will appear as a strong reflection stopping abruptly at the Key Tuffite, just like an unconformity. Rhyolite horizons do not cross the Key Tuffite and are always concordant. These criteria, in conjunction with available borehole information (white dots on Figure 5.8), were used to interpret the Key Tuffite (Figure 5.8) from the migrated 3D seismic volume. The southwestern limit of the Key Tuffite marks the interpreted location of the Daniel fault within the 3D survey region. The black dots on Figure 5.8 indicate the source and receiver locations of the seismic survey. The Key Tuffite could not be picked reliably on the southeastern and northwestern edge of the survey because of the low fold. The Key Tuffite was picked over an area of 6.6 km², between depths ranging from 130 to 1440 m. Since this horizon is not characterized by a single reflector, the Key Tuffite depth uncertainty is about 100 m and probably larger near the edges of the survey area. However, the location of the Daniel fault is well defined due to the clear truncation of reflectors.

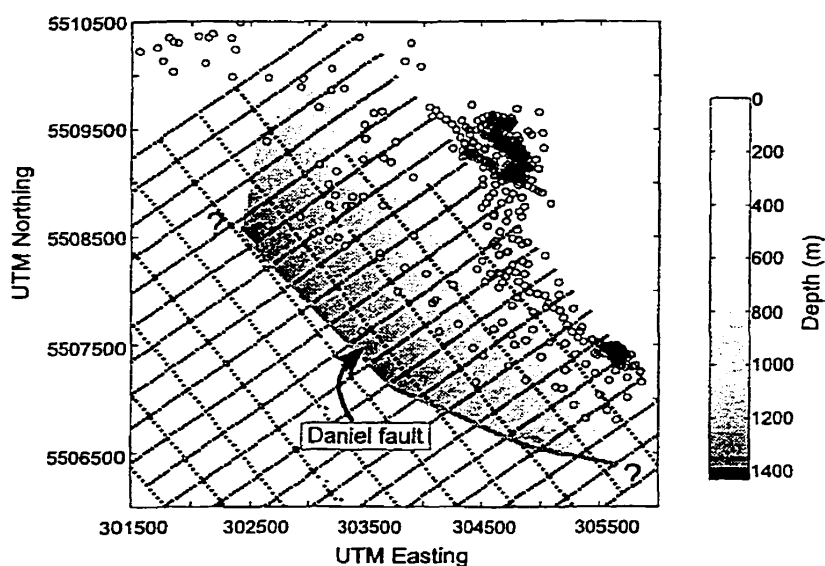


Figure 5.8: Interpreted Key Tuffite from the 3D depth migrated seismic dataset. The black dots indicate the position of shot and receivers while the white dots are the borehole locations

5.2.7.2 Imaging the Bell Allard deposit

Umigrated image

The Bell Allard ore deposit is located between 900 and 1150 m from the surface and borehole control exists in the vicinity of the deposit to depths of about 1250 m. At an early stage of data processing (brute stack with refraction static corrections applied), a zone of anomalous amplitude in the vicinity of the known ore deposit was identified at 400 ms (~1200 m). This anomaly was still present after the application of DMO corrections but was less obvious because of the enhanced reflectivity from dipping reflections. The anomaly has a lateral extent that corresponds well with the area occupied by Bell Allard and with the base of the low-grade massive sulphide lens. However, it is also only tens of meters away from a known gabbro intrusion.

In order to interpret the seismic data better, a comparison between the 3D seismic data and the synthetic response of a Bell Allard model was made. In timeslice, the Bell Allard modelled seismic response appears as a distinctive circular anomaly with amplitude versus azimuth variations (Figure 5.9a). The position of Bell Allard corresponds with the center of

the circular anomaly. Figure 5.9b shows an unmigrated synthetic section through a 3D cube structural stack along a north-south traverse (marked as A-A' on Figure 5.9a) and directly above the Bell Allard deposit. The corresponding seismic section shows south-dipping reflections (marked as R on Figure 5.9d) originating from rhyolite-gabbro and rhyolite-basalt contacts within the Lower Wabasse Group, as well as a distinct diffraction hyperbola (marked as D on Figure 5.9d) at the Bell Allard location. Note that the highest amplitudes occur on the southern flank of the hyperbola and that the same amplitude variations are observed on the synthetic section generated using the Born approximation (compare Figure 5.9b and 5.9d) (Eaton, 1999). The good match between the sections suggests that the seismic response is generated at the base of the Bell Allard deposit. Because the upper part of the deposit is sphalerite-rich (low impedance), it may not be reliably imaged and only the deep pyrite and magnetite-rich zones appear to be reflective. This observation is in agreement with physical rock property studies which predicted that pyrite and magnetite-rich ores have the highest acoustic impedances (Adam et al., 1996; Salisbury et al., 1996).

Migrated image

To compare the seismic signature with the borehole derived geological sections, a traverse matching a geological section through the deposit (Figure 5.10b) was extracted from the 3D seismic volume. To provide the context for the detailed section, the seismic traverse extended across the whole seismic volume (Figure 5.10a). On this section, the massive sulphides are not underlain by the alteration pipe and the stratigraphy is simple. This section exhibits the strongest seismic response directly associated with the massive sulphides (Figure 5.10b). The maximum amplitude along the Upper Rhyolite (Figure 5.10b) is 30% lower than the one associated with Bell Allard. The amplitude anomaly 50 ms below Bell Allard is 43% higher. This difference can perhaps be explained by the composition of the Bell Allard massive sulphides (largely sphalerite) and its smaller size compared to the underlying anomaly.

Discontinuities in the basalt-rhyolite sequence above the massive sulphides indicate the

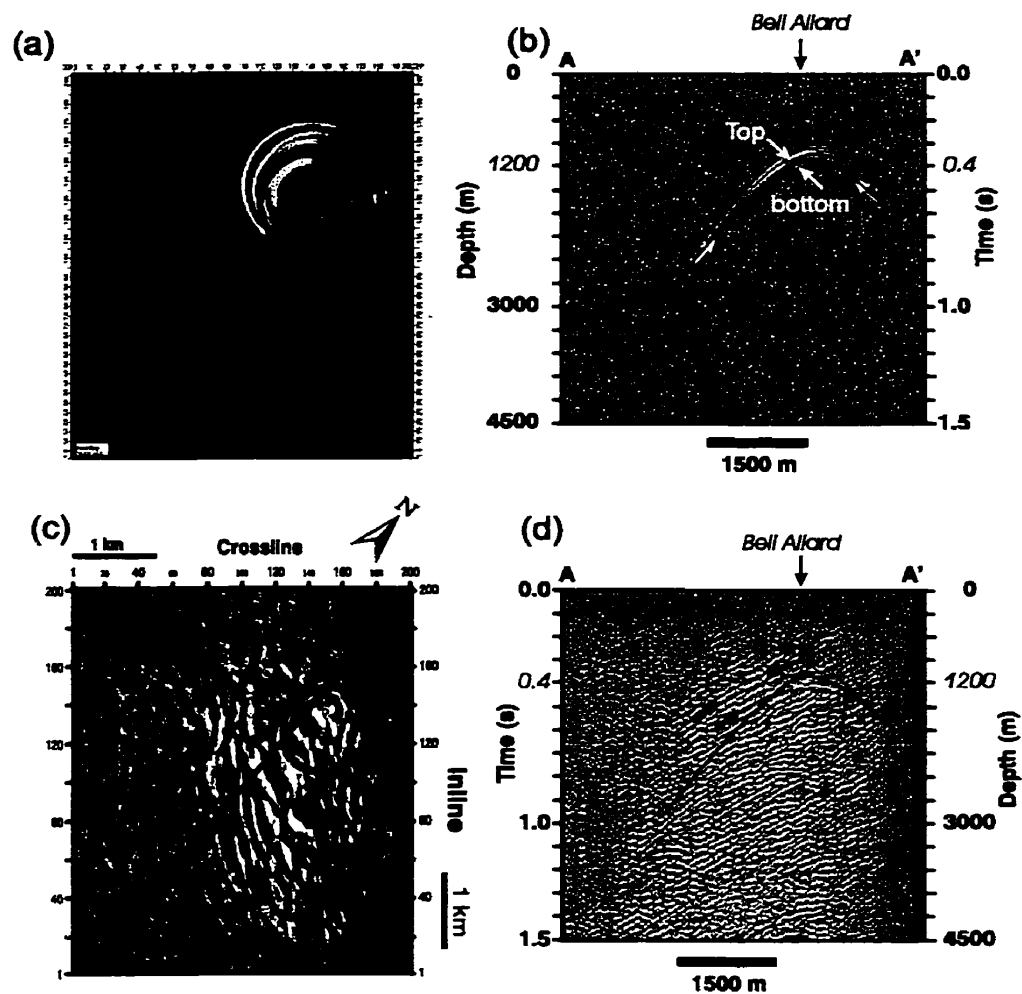


Figure 5.9: a) Unmigrated synthetic response of the Bell Allard deposit in plan view at 410 ms and b) along a north-south traverse directly above the Bell Allard deposit. c) DMO results of the Matagami 3D data for the same timeslice as (a) and d) the corresponding traverse shown in (b).

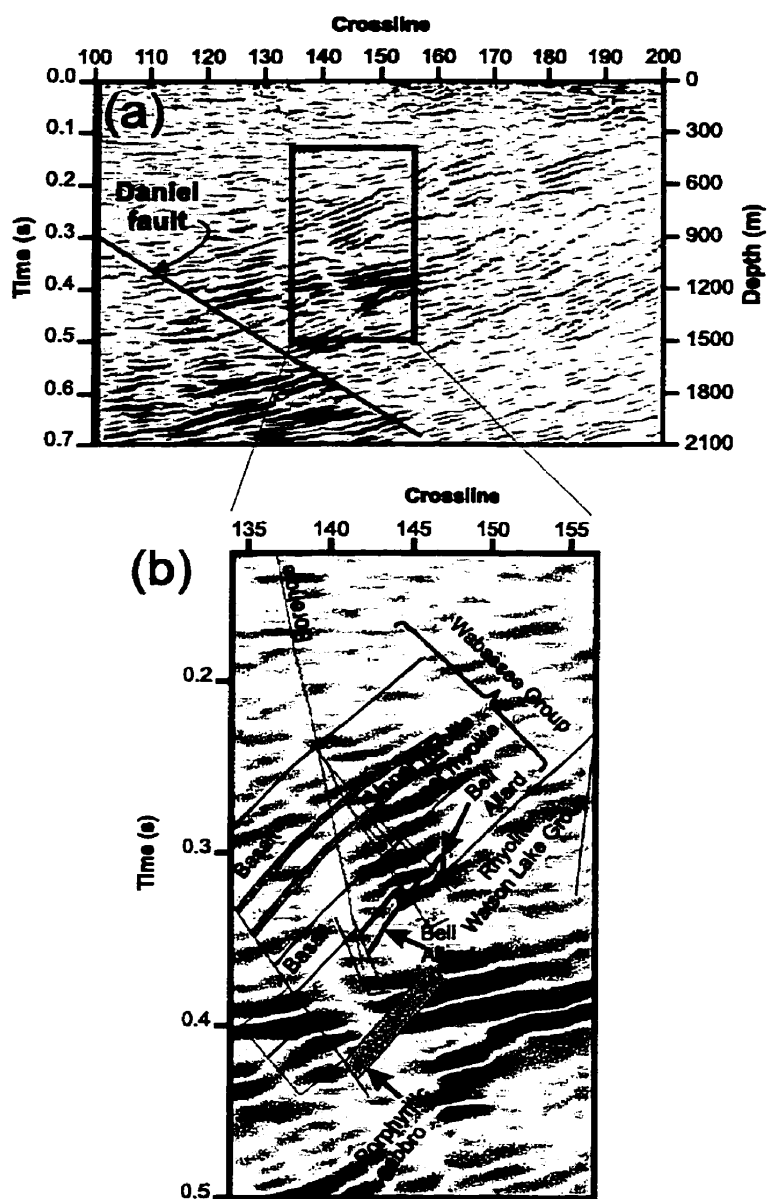


Figure 5.10: a) Seismic section coincident with a geological section through the Bell Allard deposit which has been extended to the limits of the 3D stacked volume. b) Geological section superimposed on the seismic data. Anomalous high amplitudes are found at the massive sulphide lens. Discrepancies between the dip of reflectors and the contacts interpreted on the geological section are attributed to the limited number of boreholes (red lines).

presence of faults. The high-amplitude anomaly located beneath the Bell Allard deposit appears to be fault-bounded and may correspond to the alteration pipe of the Bell Allard deposit or it may represent the signature of the regional scale gabbro intrusion. The Daniel fault is interpreted where a sudden break in reflectivity occurs. Using the available borehole and geological information, the seismic data appears to be properly calibrated and the prestack migration performed with a constant velocity of 6.1 km/s produces a reliable seismic image that correlates well with the available geological data.

The Bell Allard deposit consists of two distinct lenses underlain by an alteration zone. The mineralogy and grade vary significantly throughout the orebody and the composition of the alteration zone is still largely unknown. Our observations of the 3D seismic data suggest that sphalerite-rich massive sulphide zones do not generate the strongest reflections in the Matagami 3D stacked volume, probably because of their smaller size and lower acoustic impedance relative to the host rocks. Local pyrite-rich zones appear to be more reflective, as observed on Figure 5.10b, but they are not as reflective as the gabbro intrusions. The origin of a large amplitude anomaly below Bell Allard is still unexplained and possible interpretations are given below.

5.2.8 Discussion

5.2.8.1 Alteration zone or gabbro sills below Bell Allard?

Strong seismic amplitudes are located beneath the Bell Allard massive sulphides. This amplitude anomaly appears to be fault bounded but borehole control at this depth is limited and the cause of the anomaly is still unknown. We speculate that the strong reflections could originate from a magnetite-rich gabbro sill or from the alteration zone. A gabbro sill has been intersected below Bell Allard by a few boreholes but it is described as a porphyritic type that is generally not as reflective as the tholeiitic magnetite-rich type. Also, if the anomaly is caused by a gabbro sill, it not clear why the enhanced reflectivity is restricted to the vicinity of the ore deposit. Another hypothesis is that the alteration zone

is causing the anomaly. Several geological settings and mineralogical assemblages could explain the presence of a strong seismic reflection package in the alteration pipe of a VMS deposit. Possible explanations are: enrichment in pyrite and magnetite (Lavallière et al. 1994) or lower acoustic impedances (caused by fractures and alteration) that enhances the reflectivity at the contact with mafic intrusions. Typical alteration zones of VMS deposits may be larger in volume than the massive sulphide zones themselves. This characteristic potentially makes them a better target for exploration programs (Lavallière et al., 1994). If the VMS deposit alteration zone has a significant contrasting acoustic impedance with its host rock, then it is more likely to be imaged by a seismic survey than the sphalerite-rich massive sulphide zone.

To clarify the ambiguity regarding the origin of the amplitude anomaly underlying Bell Allard, a comprehensive petrophysical study of the alteration zone, its host rocks and, intrusions must be conducted because physical rock properties are the link between geological and seismic data, and are the key to seismic data interpretation. At present, the limited borehole control in the alteration zone has prevented the completion of the petrophysical study. As in-mine definition drilling and underground access becomes available, it will be possible to better understand the seismic signature of the Bell Allard alteration pipe.

5.2.8.2 Is 3D seismic exploration cost effective?

The impact that 3D seismic technology has had on exploration for oil and gas since the early 1980's has been monumental (Nestvold, 1992). The extra cost in data acquisition of 3D seismic surveys compared to 2D seismic surveys has been largely offset by the resulting improved drilling success rate (Greenlee, 1994). The gradual adoption of 3D seismic technology by the oil and gas industry can be illustrated by the part of its annual exploration budget that Shell Oil spent on 3D seismic surveys: from 5% in 1981 to 65% in 1990 (Nestvold, 1992). Comparatively, the conventional exploration techniques (such as electromagnetic methods) used by the mineral industry to locate deep (>500 m) ore deposits have not been very productive. For example, in the Abitibi belt, only 4 mines with summits

deeper than 500 m had been discovered before 1990. On the other hand, more than 150 mines have surface expressions or their summits are at less than 500 m depth (Lulin, 1990). While these numbers clearly depict a grim portrait for the mineral exploration industry, it is important to remember that, to justify underground production at large depths, the tonnage or grade of the deposit must be larger than at shallow depths. Consequently, the chances of finding an economic deposit decrease with depth. The current exploration technique for locating deep VMS ore deposits relies on a good geological model, drilling, and downhole electromagnetic surveys to locate conductive deposits within a 100-150 m radius around the borehole (Lavallière et al., 1994; Boivin and Lambert, 1997). However, this technique provides no drill target beyond the geologic model of the experienced explorationist. Near-surface exploration benefits from cheap magnetic and electromagnetic surveying (airborne, surface, or borehole) to locate conductive bodies. In deep exploration, these types of surveys are often limited by their lack of depth penetration or to areas where deep boreholes are available and a method that can replace the role of magnetic and electromagnetic surveys to explore at depths below 500 m in existing mining camps is required. 3D seismic surveys can potentially fulfil this role.

However, the cost is well above that of geophysical surveys the mineral industry routinely employs. The total cost of the Matagami 3D survey is estimated at \$50 000/km². And, if we consider only the area where the Key Tuffite was mapped (6.6 km²), then the cost is about \$180 000/km². Nevertheless, 3D seismic surveys are cheaper where the host-rock stratigraphy is sub-horizontal because the imaged area is larger; the budget increases with the regional dip as the survey area needs to be larger to achieve a comparable subsurface image. In 1996, the Canadian average drilling cost was \$83/m or \$83,000/km of drilling (Natural Resources Canada statistics, 1997). Thus, in the Matagami area the value of the 3D survey is equivalent to more than 2 boreholes per km² assuming that the average Key Tuffite depth is 780 m (from the Key Tuffite interpretation) in the survey area. The 3D survey has revealed one strong distinctive anomaly that correlates with the Bell Allard VMS deposit. This anomaly would have been the primary drill target and is unique in the data

volume. Thus, if we assumed that no prior drilling had been done within the grid, then the total cost of discovering Bell Allard would have been 6 M\$ (the 3D seismic survey and 42 boreholes to delineate the ore). This value compares very advantageously with the average cost of 38 M\$ (Natural Resources Canada statistics, 1997) to find and delineate an economic base-metal deposit in Canada.

The use of 3D seismic before deep diamond drilling has several advantages. Firstly, it can image flat to moderately dipping ($<45^\circ$) strata from ~ 250 m (and sometimes shallower) to several kilometers depths and help establish prospective geology and drilling targets. Secondly, it can also help define the regional geologic framework and thus reduce the number of stratigraphic boreholes. Finally, the drillholes targeted at seismic anomalies will maximize the opportunity for success of downhole electromagnetic surveys. If the borehole misses the seismic anomaly, it may still be close enough to allow the detection of the anomaly using downhole electromagnetic surveys which have a radius of investigation of about 150 m. The cost of 3D seismic surveying for mineral exploration is expected to be higher than it is for oil and gas exploration. The requirement for high fold and large source-receiver offsets to compensate for the high velocities and low reflection coefficients translate into higher acquisition cost. Also, the cost of mobilizing a large 3D seismic crew to a remote mining camp is also significant. These costs became less significant, however, if reliable deep drill targets can be identified or even if ground can be excluded as a consequence of no detection of drill targets.

5.2.9 Conclusions

Seismic methods are effective at mapping sub-surface stratigraphy in the Matagami mining camp and can provide direct detection of even small massive sulphide deposits when conditions are optimal. The seismic signature of the orebody depends on several factors: 1) the seismic survey acquisition parameters, 2) the geometry and size of the deposit, 3) ore zoning (distribution of pyrite, magnetite and other high impedance minerals), and 4) the impedance contrast between the ore and the host rock. In our case, the physical rock-

property study concluded that a strong impedance contrast exists between the deposit and the host rocks. Forward seismic modelling of a synthetic Bell Allard ore deposit predicted a characteristic seismic response that was confirmed by the actual 3D seismic survey. Results from the Matagami 3D survey suggest that partial prestack migration techniques, such as DMO, are best suited to preserve the diffraction hyperbola generated by an orebody. The DMO stack has the most characteristic response of the Bell Allard ore deposit (amplitudes and shape). On the South Flank of the Galinée anticline, units with contrasting acoustic impedances dip moderately to the southwest, allowing them to be mapped at great depths using seismic reflection methods. Although full prestack migration does not help as much in the direct detection of ore deposits, it images structures and stratigraphy that define the geological environment.

3D seismic surveys are relatively expensive ($> \$50\,000/\text{km}^2$), yet they can be warranted as an alternative to deep stratigraphic-grid drilling to explore prospective horizons at depth within existing mining camps. 3D seismic surveys are cheaper ($\sim 50\,000/\text{km}^2$) where stratigraphy is flat lying and ground surface conditions are favorable. The cost increases with the regional dip as the survey area has to be increased to achieve a comparable subsurface image. More research is required to characterise the acoustic signature of massive sulphide bodies to distinguish such targets from other non VMS-related features outlined by 3D surveys. With progress in this area and the subsequent discovery of new mineral resources, seismic reflection technology could become a routine exploration method to test for deep orebodies in VMS mining camps.

5.2.10 Acknowledgments

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Geological Survey of Canada contribution XXXXX.

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CHAPITRE 6

SYNTHÈSE

6.1 Introduction

L'étude de cas de Matagami a démontré que l'utilisation de la sismique réflexion est une méthode géophysique efficace pour cibler les forages profonds dans le camp minier de Matagami. Dans ce chapitre, une procédure d'intégration par étapes de la sismique 3D est présentée. Les limites de la méthode, une application récente et des recommandations pour des recherches subséquentes sont aussi présentées.

Les travaux de recherche dans le camp minier de Matagami ont permis d'établir une méthodologie comportant plusieurs étapes avec des points de décision pour faciliter l'intégration de la sismique réflexion 3D aux procédures normales d'exploration minière. La première étape consiste à obtenir les propriétés physiques affectant l'amplitude des réflexions sismiques (densité et vitesse de l'onde de compression) pour les unités géologiques du camp minier. S'il est établi que la cible montre un contraste d'impédance acoustique suffisant, un levé PSV permettra alors de s'assurer que la cible est réfléchive aux fréquences générées par la source sismique de surface. De plus, un levé PSV établit sans équivoque la relation entre la profondeur et le temps et par conséquent, les réflexions sismiques peuvent être directement reliées aux structures géologiques intersectées par le forage. Dans le cas où le contact cible serait réfléchif en PSV, un profil 2D permettra d'établir si le réflecteur peut être imagé sur une distance convenable et de déterminer les différents paramètres d'acquisition. Lorsqu'une image 2D satisfaisante est obtenue, un levé 3D peut être envisagé en utilisant

les paramètres du levé 2D. Le levé 3D permet alors de résoudre les ambiguïtés engendrées par une géométrie d'acquisition 2D, et ainsi imager les structures géologiques et établir des cibles de forage.

6.2 Etude pétrophysique

Cette étude est sans doute la moins onéreuse mais aussi la plus importante pour évaluer l'applicabilité de la méthode sismique réflexion dans différents environnements miniers. Les réflexions sismiques se produisent lorsque deux types de roches ayant des impédances acoustiques différentes sont juxtaposées. L'étude pétrophysique vise donc à établir la densité et la vitesse de l'onde de compression (onde P) pour les différentes unités lithologiques du camp minier. L'étude pétrophysique devrait être réalisée dans chaque camp minier pour les raisons suivantes : 1) les valeurs d'impédance acoustique dérivées d'ouvrages de compilation ne donnent aucune information au sujet de l'altération régionale ou de la fracturation des échantillons alors que ces effets peuvent affecter la densité et la vitesse sismique et, 2) le coût de l'étude pétrophysique est relativement faible comparé à celui du levé 3D. La variabilité de l'impédance acoustique des roches du camp minier de Matagami est illustrée dans le chapitre 5. Puisque que les longueurs d'ondes sismiques sont normalement de quelques dizaines de mètres, il est préférable de caractériser les unités lithologiques à une échelle comparable. Bien que différentes méthodes soient disponibles, leurs domaines d'application diffèrent. Par exemple, les mesures à haute-pression de la vitesse de l'onde P sont idéales pour obtenir la vitesse de minéraux purs. Par contre, le coût élevé, la petite taille des échantillons (quelques cm), et les fréquences élevées sont incompatibles pour définir l'impédance acoustique des lithologies à l'échelle régionale. Les mesures pétrophysiques in situ (e.g. en forage) sont moins chères. Les diagraphies utilisent des fréquences plus basses que celles utilisées en laboratoire et il est démontré (chapitre 4) que les vitesses dérivées des diagraphies soniques sont similaires à celles obtenues des PSV. Par contre, les densités mesurées en forage ne sont parfois pas calibrées, particulièrement lorsqu'il y a des sulfures (Pflug et al., 1999).

Il est donc recommandé de faire des mesures de densité en laboratoire pour déterminer la densité des roches contenant des sulfures et des oxydes (e.g. magnétite). Les avantages d'effectuer des diagraphies sont que les mesures représentent jusqu'à quelques mètres de roche (Ellis, 1987) et qu'elles produisent un grand nombre de mesures (échantillonnage au 10 cm), ce qui permet une analyse statistique significative. Pour obtenir des mesures de vitesse à une échelle encore plus proche de celle des données sismiques (~ 20 m), on peut aussi réaliser des levés utilisant un équipement de sismique réfraction placé directement sur la roche (affleurement ou sous-terre). Ces mesures vont probablement sous-évaluer les vitesses à cause des conditions locales de fracturation (e.g. à proximité des galeries de mines) ou d'altération (e.g. régolite). L'estimation des densités à la même échelle est plus problématique. Il est quand même possible de l'évaluer en effectuant un levé gravimétrique en forage ou dans des galeries de mine.

En général, les méthodes pour obtenir l'impédance acoustique des roches à partir des trous de forage ont été développées par l'industrie pétrolière. Par contre, la plupart des instruments disponibles ont un diamètre incompatible avec les trous de forage utilisés en exploration minérale. En effet, les trous de forage d'exploration minérale ont généralement un diamètre inférieur à 75 mm alors qu'ils sont au moins 5 fois plus grands en exploration pétrolière.

6.3 Profilage sismique vertical (PSV)

Les levés PSV sont particulièrement utiles pour relier les réflexions sismiques aux structures géologiques (contacts lithologiques, failles, etc.) interceptées par un trou de forage. Des applications récentes du PSV ont démontré que dans certains environnements géologiques la méthode pouvait être utilisée pour assister l'exploration minérale et identifier des cibles de forage. Des levés PSV ont imagé des gisements SMV riches en pyrite dans les camp miniers de Bathurst et de Kidd Creek (Eaton et al., 1996 ; Salisbury et al., 1997). A Kidd Creek, la méthode a aussi été modifiée pour utiliser une ligne de point de tir enregistrée à

plusieurs niveaux d'un trou de forage, produisant ainsi un volume de données sismiques. Ce levé a enregistré une réflexion provenant d'un contact vertical rhyolite-andésite et une forte anomalie d'amplitude provenant d'une lentille de pyrite. Les levés PSV sont donc capables d'imager certains type de sulfures massifs et des contacts verticaux situés à des distances de près de 1 km d'un trou de forage (Eaton et al., 1996). Dans le camp minier de Matagami, le pendage modéré des contacts lithologiques et l'impédance acoustique plus faible des sulfures massifs riches en sphalérite, ne favorisent pas l'utilisation du PSV en exploration. D'autre part, l'acquisition d'un PSV requiert un trou de forage situé à une certaine distance de la cible pour favoriser la détection des diffractions : car, lorsque le trou de forage est trop proche de la cible, les réflexions sont proches des arrivées directes et il est alors difficile de les identifier. Bien que la méthode de PSV peut être un outil d'exploration valable dans certains cas, elle est encore peu répandue et par conséquent, elle souffre de méthodes d'acquisition, de traitement de données et d'interprétation non conventionnelles. Ainsi, il est recommandé d'utiliser les levés PSV seulement pour identifier l'origine des réflexions sismiques.

6.4 Sismique 2D

Les levés sismiques 2D réalisés dans les roches cristallines enregistrent des événements qui proviennent du dessous du profil mais aussi de chaque côté de la ligne sismique (Zaleski et al., 1997). Ainsi une structure verticale située à une distance de 1 km et parallèle au profil sismique aura la même signature sismique qu'un réflecteur horizontal situé 1 km de profondeur sous le profil sismique. Bien que cet effet est présent dans un environnement de roche sédimentaire, il est rehaussé dans les roches cristallines à cause de l'important contraste de vitesse présent entre le socle et le mort-terrain. À cette interface, des ondes sismiques voyageant horizontalement (c'est un cas extrême) sont réfractées dans le mort-terrain et ont une composante verticale dont l'amplitude est fonction du contraste de vitesse à l'interface socle/mort-terrain. Ce phénomène, qui s'explique par la théorie de base de propagation des ondes sismiques (loi de Snell), a été illustré par l'acquisition de PSV au

niveau de l'interface socle/mort-terrain (Lash, 1986 ; Adam et al., 2000). Etant donné que les ondes sismiques changent de direction dans le mort-terrain, l'acquisition de données sismiques 3 composantes à la surface ne permettra pas de déterminer la direction d'une onde sismique dans le socle. C'est pourquoi Wu (1995) a proposé l'utilisation de lignes sismiques sinueuses comportant des tournants abrupts pour estimer le pendage réel des réflecteurs. L'application de la technique de traitement de données développée par Wu (1995) a permis la localisation d'une anomalie de forte amplitude dans la région de Onaping (bassin de Sudbury). Toutefois, ce type de traitement de données est non-conventionnel et prend beaucoup de temps. Alors que la sismique 2D peut jouer un rôle important pour établir la stratigraphie profonde à l'échelle d'un camp minier, elle ne permet pas de définir des cibles de forage précises. D'autre part, l'importance d'établir les paramètres optimum d'un levé sismique 2D tient au fait que les paramètres d'acquisition d'un levé sismique 3D en dépendent. En effet, avant d'entreprendre l'acquisition d'un levé 3D et d'en établir le coût, il faut acquérir une ligne 2D produisant une image sismique adéquate.

6.5 Sismique 3D

La sismique réflexion 3D est la méthode qui permet le mieux de cibler les trous de forage en exploration pétrolière. En exploration minérale, elle a été appliquée dans trois camps miniers canadiens : Sudbury (Trillabel), Matagami (Bell Allard), et Bathurst (Half-mile Lake). Ces trois camps miniers présentaient des contextes géologiques et des conditions de surface différentes. Dans le camp minier de Sudbury, le levé 3D a permis d'identifier le gisement de Trillabel et une seconde anomalie associée à un intrusif de gabbro contenant de la magnétite (Milkereit et al., 1997). Dans cette région, le fort pendage des unités stratigraphiques ($\sim 60^\circ$) ne favorise pas l'obtention d'images sismiques de qualité mais il facilite l'identification des diffracteurs associés, entre autres, aux sulfures massifs. Dans le camp minier de Matagami, le pendage modéré ($\sim 45^\circ$) avantage la méthode sismique 3D et de fortes réflexions associées aux contacts lithologiques sont imagées. La qualité de l'image sis-

mique permet l'identification de failles et de contacts importants pour l'exploration minérale mais les réflexions des contacts lithologiques cachent partiellement la réponse des sulfures massifs. Les levés sismiques du camp minier de Bathurst (Salisbury et al., 1997; Gingerich et al., 2000) montrent peu de réflexions provenant de contacts lithologiques d'étendues régionales. De plus, les sulfures massifs du camp de Bathurst contiennent typiquement de grande quantité de pyrite dont l'impédance acoustique est plus élevée (~ 40) que celle des autres sulfures communs. Comparativement, les sulfures des camp miniers de Matagami et de Sudbury sont enrichis respectivement en sphalerite et en pyrrhotite et contiennent peu de pyrite. Le levé 3D de Bathurst se trouve donc dans un environnement géologique plus favorable que les deux autres. Des forages pour vérifier deux anomalies sismiques ont permis d'identifier une zone de déformation à une profondeur de 1.6 km et une lentille de sulfures massifs sub-économique enrichie en pyrite d'une épaisseur de 50 m et à une profondeur de 1 km (Gingerich et al., 2000). Il est clair que la performance de la sismique 3D dépend fortement du contexte géologique et du contraste d'impédance de la cible. Par exemple la sismique 3D ne permettra pas de bien imager des contacts dont le pendage excède 60° alors que la détection directe des sulfures massifs riches en pyrite dans un environnement felsique (impédance acoustique faible) sera facilitée. Ce sont donc les études préliminaires (pétrophysiques, PSV, et sismique 2D) qui permettront d'évaluer les chances de succès d'un levé sismique 3D en exploration minérale.

6.6 Directions de recherche futures

Le levé 3D de Matagami a démontré la force de la méthode à imager la stratigraphie profonde et à identifier une forte anomalie d'amplitude possiblement associée à la cheminée d'altération du gisement Bell Allard. La cause exacte de l'anomalie n'est pas encore expliquée. La complexité géologique d'une cheminée d'altération d'un gisement SMV, tel que décrit par Lavallière (1994), pourrait se traduire par une hausse de l'impédance acoustique à cause de la présence de minéraux de forte impédance acoustique (e.g. pyrite, magnétite)

ou une baisse de l'impédance acoustique due à la fracturation et la présence de minéraux d'altération (e.g. talc). Une étude pétrophysique pour caractériser les cheminées d'altération de gisement SMV devrait donc être entreprise pour en comprendre la réponse géophysique.

Des études pétrophysiques sur d'autres types de gisement important seraient aussi utiles pour établir leur détectabilité par méthode sismique 3D. En somme, les études pétrophysiques sont la clé pour interpréter, modéliser, et planifier tout levé géophysique. Elles ne devraient donc jamais être négligées puisque le choix même d'une méthode géophysique d'exploration adéquate en dépend.

CONCLUSIONS

L'étude de cas de Matagami a démontré qu'une méthodologie d'implémentation de la sismique 3D en 4 phases était nécessaire pour garantir le succès de l'approche. Les mesures pétrophysiques ont permis d'identifier la cause des réflecteurs : les contacts gabbro-rhyolite et les sulfures massifs riches en pyrite ou magnétite. Le levé PSV a démontré que le gisement de Bell Allard produisait une forte réflexion sismique mais que la technique ne pouvait pas être utilisée comme outil d'exploration dans ce camp minier. Les profils sismiques (2D) ont permis d'établir les paramètres d'acquisition optimum et ont démontré que les contacts lithologiques et les failles pouvaient être imagées à des profondeurs excédant 3 km. Ces paramètres ont ensuite été utilisés pour l'acquisition d'un levé 3D qui a cartographié une région prospective de 6.6 km² et identifié de nombreuses structures géologiques importantes pour l'exploration minérale dans le camp minier de Matagami (i.e. faille Daniel, Tuffite Clé, rhyolite de Dumagami, faille synvolcanique). Finalement, il a imagé une anomalie d'amplitude à 100 m sous le gisement de Bell Allard interprétée comme une zone enrichie en pyrite de la cheminée d'altération du dépôt ou un sill de gabbro. Le développement de technique de traitement de données permettant de rehausser les diffractions causées par les sulfures massifs pourrait aussi faciliter l'adoption de la méthode dans les camps miniers où les unités lithologiques sont réfléchives. Une meilleure compréhension des propriétés physiques des gisements de type SMV et d'autres types de gisement produisant de grande quantité de métal (e.g. SEDEX) permettront d'optimiser les techniques d'exploration profondes et ainsi prolonger la vie de nombreux camps miniers.

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