Review

A review of reflection seismic investigations in three major metallogenic regions: The Kevitsa Ni–Cu–PGE district (Finland), Witwatersrand goldfields (South Africa), and the Bathurst Mining Camp (Canada)

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A B S T R A C T

Effective exploration for mineral deposits depends on a sound understanding of the processes and geological structures that contributed to their formation. The reflection seismic method has proven to be a powerful tool that provides a high-resolution image of the subsurface and information about structural and lithological relationships that control mineral deposits. The method has also become an attractive geophysical tool for deep exploration and mine planning. In this paper, we review the use of reflection seismic methods to obtain a better understanding of the architecture and ore-forming processes of three diverse mineral regions: the Kevitsa Ni–Cu–PGE district in Finland, the goldfields of the Witwatersrand Basin South Africa, and the Bathurst Mining Camp, Canada. Seismic data, both 2D and 3D, from the Kevitsa deposit clearly image the 3D geometry of the ore-bearing intrusion and provide information about its relationship to the host rock units and nearby intrusions within a larger tectonic framework. 3D seismic data from the Witwatersrand Basin not only provide clear images of major structures, including a distinct reflection that acts as a marker horizon for the gold-bearing reef, but also provide information that may be useful in resolving a long-standing controversy regarding the origin of the gold in the Basin. For example, it might be possible to show that dykes formed impermeable barriers, thereby falsifying the epigenetic hydrothermal models. 2D and 3D seismic data from the Brunswick No. 6 area in the Bathurst Mining Camp suggest that the Brunswick horizon (which contains the bulk of the massive sulfide and associated iron deposits) occurs within a reflective package that extends down to at least 6–7 km depth.

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1. Introduction

Reflection seismic methods are used to provide high-resolution images of subsurface structures and lithological boundaries, as well as information about the physical properties of rocks, such as their density and seismic velocity. To date, several hundreds of 2D lines and tens of 3D surveys have been acquired and reported in major metallogenic provinces worldwide (Fig. 1, e.g., Adam et al., 2003; Campbell and Peace, 1984; Clowes et al., 1984; Dehghannejad et al., 2010, 2012a, 2012b; Durrheim et al., 1991; Eaton et al., 2010; Ehsan et al., 2012; Evans et al., 2003; Goleby et al., 2002; Juhlin et al., 2002; Korja and Heikkinen, 2005; Malehmir et al., 2006, 2007, 2009, 2011, 2012a; Milkereit and Eaton, 1998; Milkereit et al., 1996; Odgers et al., 1993; Pretorius et al., 1989; Ruskey, 1981; Stolz et al., 2004; Tryggvason et al., 2006; Urosevic et al., 2005; Williams et al., 2004).

The explorer has a range of geophysical methods to map the subsurface. His choice depends on many factors, including the physical properties and depth of the target body, the properties of the host rock and overburden, and the logistic requirements and cost of surveys. Potential field and electromagnetic methods have been widely and successfully used to search for metallic ore bodies. However, reflection seismic methods usually provide a superior trade-off between resolution and depth. This technology, especially 3D seismics, is fast becoming an established method for deep exploration and mine planning (Malehmir et al., 2012b and references therein). In addition, the present trend in exploration and exploitation of mineral resources at greater depths favors the use of seismic methods, not only for targeting deep-seated mineral deposits and for deep mine planning, but also for gaining a better understanding of the overall architecture of mineralized regions (e.g., Goleby et al., 2002; Kukkonen and Lahtinen, 2003; Kukkonen et al., 2011; Malehmir et al., 2007; Willman et al., 2010). This information is especially important when formulating strategies to explore mining camps where most shallow deposits have been found and exploited. Fig. 2 shows major base metal discoveries in Western countries until 2007. The figure clearly reveals that targets are getting deeper, especially in the so-called brownfields (i.e., mature) mining camps.

Reed (1993) provided a comprehensive review of reflection seismic surveying for mineral exploration applications. Milkereit et al. (1996) investigated the petrophysical properties of volcanogenic-hosted massive sulphide (VHMS) deposits (typically high density, and sometimes high velocity) and the application of seismic methods to explore for them. A number of papers were subsequently published presenting the successful application of seismic methods for hard rock exploration (Eaton et al., 2003 and references therein). Recently, Malehmir et al. (2012b) reviewed past and recent applications of seismic methods for mineral exploration and mine planning in Australia, Europe, Canada and South Africa. The current paper has a different focus. Here, we demonstrate how reflection seismic methods can be used to gain a better understanding of mineralized regions.
understanding the ore genesis in three major mining regions, namely the Kevitsa Ni–Cu–PGE district in northern Finland, the gold-bearing conglomerates of the Witwatersrand Basin in South Africa, and the Brunswick No. 6 base metal deposit in the Bathurst Mining Camp, Canada. These mining regions contain world-class mineral deposits, such as the super-giant Brunswick No. 12 VHMS deposit in Canada and the South Deep gold mine in the Witwatersrand goldfields. The development of the Kevitsa Ni–Cu–PGE deposit (mining commenced in summer 2012 and is planned to continue for the next 20–30 years) and the recent discovery of the nearby Sakatti Ni–Cu deposit (Jim Coppard, 2011, personal communication) are examples of favorable geological conditions in the Finnish Lapland.

We commence with a brief review of the basic principles of seismic methods. We then present three case studies. In each study we (1) review existing 2D and 3D seismic data, (2) provide information about the relationships between the mineralization and structural and lithological features, and (3) analyze existing mineralization scenarios/models in the light of seismic data. For example, we show how reflection seismic data may be used to: establish a link, if any, between dykes and faults and gold mineralization in the Witwatersrand Basin; determine the depth extent of the Brunswick horizon that hosts major VHMS deposits; and map the 3D geometry of the ore-bearing Kevitsa mafic–ultramafic intrusion that controls the overall bulk mineralization, and features of its larger tectonic context.

2. Reflection seismic methods

The acquisition and processing of reflection seismic surveys depend on the site conditions (e.g., accessibility, topography, and thickness of the weathered layer) and the geology (e.g., rock properties, steepness of dips and geological complexities such as tight folding). 2D surface seismic surveys are often implemented to contain costs. However, 2D seismic data are challenging to interpret, especially in complex mining areas where the data are often acquired along crooked lines and the geological structures are in fact 3D (Malehmir and Juhlin, 2010; Malehmir et al., 2009; Nedimović and West, 2003; Wu, 1996; Zaleski et al., 1997). In these situations, the ideal solution is a 3D survey.

The strength of the seismic reflection that arises at the boundary between two geological entities depends on the contrast in the acoustic impedance (product of velocity and density). Eaton et al. (2010) discovered the strong reflective character of VHMS deposits in typical host rock environments when laboratory measurements for acoustic properties were carried out during the Lithoprobe project (Salisbury et al., 1996). Salisbury et al. (1996, 2003) systematically measured the velocities and densities of major mineral deposits and their host rocks. They showed that most metallic deposits lie far to the right of the Nafe–Drake curve in cross plots of velocity against density, mainly due to their very high density. Fig. 3 shows average velocity and density values obtained from the study areas discussed in this paper superimposed on the results of Salisbury et al. (2003). For example, note that VHMS deposits tend to place at different parts of the cross plot, depending on their mineralogy and in particular their pyrite content (Bellefleur et al., 2012; Dehghannejad et al., 2012b; Duff et al., 2012; Malehmir and Bellefleur, 2009; Malehmir et al., 2013; White et al., 2012). Also, the cross plot illustrates how host rock velocities increase from felsic to ultramafic rocks. For example, the Kevitsa main intrusion has an average P-wave velocity of 7500 m/s, while the Ventersdorp Supergroup Iava and Central Rand Group quartzite (which form the hanging- and footwall of the gold-bearing Ventersdorp Contact Reef in the Witwatersrand Basin) have P-wave velocities of approximately 6500 m/s and 5700 m/s, respectively.

In addition to the prerequisite of significant acoustic impedance contrast, the successful imaging of mineral deposits and their host rock structures depends on the dimensions and geometry of the reflectors. The resolution of seismic imaging depends on the seismic wavelength, which depends on the seismic velocity of the rocks and the frequency of the seismic pulse. The Earth absorbs higher frequencies more rapidly than lower frequencies. Hence the seismic wavelength increases with depth. The seismic waves used to image a target at a depth of 1000 m typically have lengths of 50–100 m. Consequently the top and bottom of the target will only be resolved if it is thicker than about 20 m (typically a quarter of the wavelength), while the lateral extent can only be accurately determined if it is wider than 350 m (i.e., the width of the first Fresnel zone). Targets thinner than 20 m can still be detected, but their amplitude will be mainly dependent on the geometry of the target and not solely on the impedance contrast. Targets laterally shorter than 350 m can also be detected, but the response may be a combination of reflections and diffractions (Bellefleur et al., 2012; Bohlen et al., 2003;
Most of the curs within the main part of the intrusion; the stational to the silicate mineral crystals. The sul rich in nickel and copper with signifi pyrrhotite, chalcopyrite, pentlandite, and numerous platinum group the Kevitsa intrusive complex, which contains up to about 5% sul rocks form the shallower southern part (Figs. 4 and 5). The disseminat part of the complex (the Kevitsa main intrusion) is characterized by ol-

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volcanic rocks of the Central Lapland Greenstone Belt, and is just

open pit mining by Kevitsa Mining Oy/First Quantum Minerals Ltd. commenced in June 2012. The final pit depth is planned to be 550–600 m. The estimated ore reserves of the Kevitsa intrusion are about 240 Mt (using a nickel cut-off grade of 0.1%), with low-grade metal concentrations of Ni 0.30 wt.% and Cu 0.41 wt.%

Gregory et al., 2011). The expected life-of-mine is 20–30 years.

The Kevitsa intrusion is emplaced within layered sedimentary and volcanic rocks of the Central Lapland Greenstone Belt, and is just

south of the large 2.4 Ga Koitelainen layered intrusion (Mutanen and Huhma, 2001), and west of the Satovaara intrusion (age unknown). The Kevitsa intrusive complex has an approximately oval surface expression with a northeast–southwest trending long axis. The northern part of the complex (the Kevitsa main intrusion) is characterized by olivine pyroxenites. Gabbros and pyroxenites interlayered with country rocks form the shallower southern part (Figs. 4 and 5). The disseminated sulfide Ni–Cu–PGE deposit occurs in the olivine–pyroxenite part of the Kevitsa intrusive complex, which contains up to about 5% sulfide. Most of the finely disseminated sulfides occur as granular masses interstitial to the silicate mineral crystals. The sulfides consist mainly of pyrrhotite, chalcopyrite, pentlandite, and numerous platinum group minerals of lesser economic significance. Several types of mineralization have been identified (Fig. 6): the normal or main type is disseminated, rich in nickel and copper with significant PGE and gold contents, and occurs within the main part of the intrusion; the “false ore” refers to the predominance of uneconomic pyrrhotite, and occurs mostly at the margins of the intrusion; while contact-related and possibly remobilized types are usually massive to semi-massive, and occur at or below the basal contact of the intrusion. The main mineralization is thought to be lithologically controlled, with minor structural control. Mutanen (1997) attributes the formation of the regular and false ore to contamination by variable amounts of komatiitic material and S- and C-rich metasediments. However, currently there is no consensus on the genesis.

3. Seismic investigations at the Kevitsa mafic–ultramafic Ni–Cu–PGE deposit

Kevitsa is a large disseminated sulfide Ni–Cu–PGE deposit hosted by the Kevitsa mafic–ultramafic intrusion in northern Finland (Fig. 4) and dated as about 2.06 Ga old (Mutanen, 1997; Mutanen and Huhma, 2001). The Kevitsa deposit was first discovered by the Geological Survey of Finland in 1987. Open pit mining by Kevitsa Mining Oy/First Quantum Minerals Ltd. commenced in June 2012. The final pit depth is planned to be 550–600 m. The estimated ore reserves of the Kevitsa intrusion are about 240 Mt (using a nickel cut-off grade of 0.1%), with low-grade metal concentrations of Ni 0.30 wt.% and Cu 0.41 wt.% (Gregory et al., 2011). The expected life-of-mine is 20–30 years.

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3.1. Kevitsa intrusion and its associated mineralization

More than 400 hundred diamond holes have been drilled in the Kevitsa area, but most are concentrated close to the known deposit and do not provide a comprehensive understanding of the extent of the intrusion. The basal contact of the intrusion is penetrated by only about 30 drill holes, most of which are shallow. A better knowledge of the geometry of the intrusion would provide a framework for near-mine and deep exploration in the area. An exact knowledge of the basal contact of the intrusion would also provide an exploration target for the contact-type mineralization that is often more massive and highly rich in Ni–Cu (Fig. 6).

The Kevitsa main deposit is thought to be primarily lithologically controlled. The most recent model (Gregory et al., 2011) suggests that the Kevitsa area was the focus of multiple, laterally discontinuous and internally differentiated magma pulses with plagioclase- and orthopyroxene-rich layers at the top (often fine-grained plagioclase-bearing olivine websterite), olivine websterite in the middle, and clinopyroxene- and olivine-rich at the base (olivine pyroxenite). The mineralization is concentrated towards the base of the pulses. Thus, the extent of these pulses is an important spatial control on the extent of the economic mineralization. However, identification of the individual pulses is complicated by the presence of a rock that has been historically described as “metaperidotite” in the drill core logs. The “metaperidotite” label has
been mainly used for widespread amphibole-alteration of olivine–pyroxenites, but it also includes other rock protoliths. Thus, further evidence is needed in order to better understand the ore genesis at Kevitsa.

While the surface geology indicates that the Kevitsa intrusive complex is relatively undeformed along its southern and northern margins, its eastern margin was modified by the Satovaara Fault Zone (Figs. 4 and 5) during the Svecofennian orogeny at about 1.9–1.8 Ga (Gregory et al., 2011). Consequently, the Kevitsa resource area is overprinted by numerous structures that developed during the evolution of the Satovaara Fault Zone (Fig. 4). The associated shear zones and faults offset the disseminated mineralization, and the structural evolution at Kevitsa has resulted in re-mobilization of the sulfides. However, structures are not believed to be a primary control of the Kevitsa mineralization, their role being limited to local modification (Gregory et al., 2011). The exception is the location of the intrusion itself, which is thought to have been controlled by one or more major structures at depth, although these have not been identified.

On a more regional scale, questions regarding the relationship between the Kevitsa intrusion and other intrusions in its vicinity remain, in particular about its relationship to the Koitelainen intrusion to the north and the Satovaara intrusion to the east. The regional northeast–southwest trending Satovaara Fault Zone separates the Kevitsa intrusive complex from the Satovaara intrusive complex (Figs. 4 and 5). It has been suggested that the Kevitsa intrusive complex and the Satovaara complex are parts of one original intrusion (Mutalen, 1997). If so, the Satovaara intrusion could potentially host similar deposits to the Kevitsa intrusion.

3.2. Reflection seismic data

In December 2007, a series of 2D reflection seismic profiles (Koivisto et al., 2012; Kukkonen et al., 2009) was acquired in the Kevitsa area as a part of the HIRE project (High Resolution Reflection Seisics for Ore Exploration 2007–2010; Kukkonen et al., 2011) of the Geological Survey of Finland and its mining industry partners. The Kevitsa 2D seismic survey consists of four connected survey lines (lines E2, E3, E4 and E5; Fig. 4) between 6 and 11 km long (Table 1). The aims of the survey were to delineate the overall extent of the ore-bearing Kevitsa ultramafic intrusive complex, study the seismic response of the disseminated ore deposit, search for indications of new ore deposits, and to extract structural information at depth that may be associated with mineralization. In 2010, the initial positive results of the 2D seismic survey led Kevitsa Mining Oy/First Quantum Minerals Ltd. to initiate a 3D reflection seismic survey (Table 1) for mine planning and deep mineral exploration purposes (Malehmir et al., 2012a). The main objective of the 3D seismic survey was to image major fault and fracture zones critical for geological planning of the mine. The 3D seismic survey is limited to the closer vicinity of the known deposit, while the 2D seismic survey was designed to provide a more regional view of the Kevitsa intrusive complex (Fig. 4). Prior to the 3D survey, a multi-offset and multi-azimuth VSP (vertical seismic profiling) survey was conducted to provide information about
the steeply dipping to sub-vertical structures that could not be imaged by the 3D surface seismic data. This survey was performed in borehole KV28, the deepest borehole at the location of the planned open pit (Fig. 4). Details about the seismic data acquisition, processing and interpretation of the results can be found in Koivisto et al. (2012) and Malehmir et al. (2012a).

3.3. Seismic constraints

The main aims of the 2D and 3D seismic surveys were to delineate the shape and extent of the ore-bearing Kevitsa intrusion and the geometry of some of the host rock and surrounding units, and extract information about the larger-scale structures and structures important for mineralization.
for mine-planning purposes. The 2D and 3D seismic data were used to create a 3D lithological and structural model of the area (Koivisto et al., in preparation), thus giving valuable insight to the architecture of the whole complex (Figs. 7 and 8).

The information on the extent of the ore-bearing Kevitsa intrusion can be used for more effective exploration in the area. The base of the Kevitsa intrusion is particularly clear in the northern and western sectors where it is defined by continuous reflectors (R1 in Fig. 7). Toward the east, the base is mostly defined by disruption of the reflectors internal to the intrusion. The 2D seismic data, which extends beyond the 3D seismic study, reveal that the prominent reflectors at the base of the intrusion continue deeper toward the southwest (R2 in Fig. 7). This has been interpreted as a previously unknown southern continuation of the intrusion. Furthermore, the data reveal strong reflectors at the base of the intrusion that have been penetrated by two deep drill holes in the area. These drill holes reveal contact-type mineralization at the onset of the reflectors (KV297 and KV280 in Fig. 6). Thus, the seismic data can be directly used for exploration of the contact-type mineralization. The 3D seismic data help to define the 3D geometry of the intrusion as shown in Fig. 8A.

The use of the reflection seismic method for direct mineral exploration depends on the specific seismic signature of the mineralized targets (Fig. 3). It is unlikely that the Kevitsa deposit would be associated with distinct reflectivity solely attributed to increased sulfide contents because it is low-grade disseminated ore. Nevertheless, at the deposit scale, the economic mineralization occurs within a spatially restricted reflectivity zone within the ore-bearing olivine pyroxenite part of the Kevitsa intrusion (R3 in Fig. 7). The internal magmatic layering described above is similarly restricted to the northeast of the intrusion. Outside of this area, drill holes penetrate up to 1 km of homogeneous, although altered, olivine pyroxenite, without encountering economic mineralization. We believe that the internal reflectivity in the seismic data mirrors this zone of multiple magma pulses that have been associated with the occurrence of the economic mineralization. Based on drill hole data (see details in Koivisto et al., 2012; Malehmir et al., 2012a), the often fine-grained tops (plagioclase-bearing olivine websterite) of the individual pulses could be reflective when in contact with a more coarse-grained base of another pulse with olivine pyroxenite composition (Fig. 8B). Generally, the base of a magma pulse is associated with stronger mineralization. Sulfide content increases the density, which in turn should further strengthen the contrast in acoustic impedance relative to the generally lower-density top of the next magma pulse below. Thus, the seismic data can be used to delineate a near-mine exploration envelope, based on the extent of the internal reflectivity within the olivine–pyroxenite part of the intrusion. In particular, the reflectivity zone continues below the known mineralization, thus indicating continuation of the mineralization at depth. Very recently, a deep zone of homogeneous, diffuse reflectivity identified on 2D line E5, similar in character to parts of the Kevitsa intrusion, has been drilled below hundreds of meters of country rock, and confirmed to be another olivine pyroxenite intrusion. At this stage no internal layering has been encountered, nor any mineralization, lending more credibility to the hypothesis that the former controls the latter.

The seismic data also reveal a complicated pattern of faults bracketing and crosscutting the Kevitsa intrusion as a whole and at the deposit scale. Some of these faults (Fig. 8) cross the planned open-pit mine at depths of about 300–500 m, and most likely continue to surface above the depth of the seismic imaging capability. These faults are therefore critical for geotechnical planning of the mine. The pit walls will be steep because of economic and environmental restrictions, and thus it is important that geologic structures transecting the open pit, in particular those sub-parallel to the pit walls, are well understood and mapped in the subsurface. On the other hand, some of the major structures identified in the seismic sections may potentially be related to the emplacement of the Kevitsa intrusion as a whole.

The 2D seismic data also indicate a possible relationship between the Kevitsa intrusive complex and nearby Satovaara complex. The reflections associated with the base of the Kevitsa intrusion are abruptly interrupted by the Satovaara Fault Zone, whereas discontinuous reflectivity characterizes the fault zone, and more continuous reflectivity appears again beneath the Satovaara intrusive complex (R4 in Fig. 7). Our interpretation of the basal contact of the Satovaara intrusion indicates a shallower base than for the Kevitsa complex. However, the seismic data do not clearly indicate two separate intrusions, and we think that the data might actually suggest that the two complexes are parts of a once-continuous intrusive complex, now separated by the major Satovaara Fault Zone. If so, this could further indicate that the Satovaara complex potentially hosts similar deposits to the Kevitsa intrusion. However, only a few holes have been drilled into the Satovaara complex, and more holes are needed to establish

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**Table 1**

Main reflection seismic data acquisition parameters for the Kevitsa 2D and 3D data (2007 and 2010, respectively), Brunswick 2D and 3D data (1998 and 2000, respectively), and the Witwatersrand Basin 3D data (the 2003 Kloof–South Deep seismic surveys).

<table>
<thead>
<tr>
<th>Parameter/region</th>
<th>Kevitsa</th>
<th>Brunswick No. 6</th>
<th>Witwatersrand Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey type</td>
<td>2D crooked&lt;sup&gt;1&lt;/sup&gt;</td>
<td>3D orthogonal&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2D crooked&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Recording system</td>
<td>1/0-4</td>
<td>SERCEL408/Seistronix</td>
<td>SERCEL388</td>
</tr>
<tr>
<td>No. of active channels</td>
<td>402</td>
<td>864</td>
<td>481</td>
</tr>
<tr>
<td>Maximum offsets</td>
<td>2500 to 5000 m</td>
<td>1700 m</td>
<td>4800 m</td>
</tr>
<tr>
<td>Total survey length/area</td>
<td>~33.7 km</td>
<td>~9 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>~28 km</td>
</tr>
<tr>
<td>Source</td>
<td>Dynamite</td>
<td>VIBSHIP and dynamite</td>
<td>Dynamite</td>
</tr>
<tr>
<td>Charge size/depth</td>
<td>0.125–0.25 kg/1–2 m</td>
<td>0.5 kg/3 m</td>
<td>0.5 kg/6 m</td>
</tr>
<tr>
<td>Source interval</td>
<td>50 m</td>
<td>45 m</td>
<td>40 m</td>
</tr>
<tr>
<td>No. of shots</td>
<td>~650</td>
<td>~3300</td>
<td>~770</td>
</tr>
<tr>
<td>Geophone frequency</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Receiver interval</td>
<td>12.5 m</td>
<td>15 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Nominal fold</td>
<td>50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>No. of shot lines</td>
<td>~34</td>
<td>~15</td>
<td>~45</td>
</tr>
<tr>
<td>Shot line spacing</td>
<td>~80 m</td>
<td>~400 m</td>
<td>~450 m</td>
</tr>
<tr>
<td>No. of receiver lines</td>
<td>~35</td>
<td>~28</td>
<td>~45</td>
</tr>
<tr>
<td>Receiver line spacing</td>
<td>~70 m</td>
<td>~290 m</td>
<td>~400 m</td>
</tr>
<tr>
<td>No. of active receiver lines per patch</td>
<td>~9 lines×96 active channels</td>
<td>~12 lines×288 active channels</td>
<td>12 lines×108 active channels</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1 ms</td>
<td>1 and 2 ms</td>
<td>2 ms</td>
</tr>
</tbody>
</table>

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<sup>1</sup> Koivisto et al. (2012).  
<sup>2</sup> Malehmir et al. (2012a).  
<sup>3</sup> Malehmir and Beliveau (2010).  
<sup>4</sup> Cheraghli et al. (2011).  
<sup>5</sup> Cheraghli et al. (2012).  
<sup>6</sup> Manzi et al. (2012a).

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The exact relationship of this complex to the Kevitsa intrusive complex. It should be also noted that a detailed interpretation of the Satovaara Fault Zone and continuation of the Kevitsa intrusion on E2 is complicated by a sharp curve in the survey line (Fig. 4).

4. Seismic constraints on models of ore genesis in the Witwatersrand Basin

The Mesoproterozoic Witwatersrand Basin of South Africa is the world’s largest known accumulation of gold, and has yielded more than a third of the gold ever mined. Gold-bearing conglomerates were discovered near modern-day Johannesburg in 1886. The outcrop was traced along the perimeter of the Witwatersrand Basin, and the gravity and magnetic methods were used to explore for ore bodies where the Witwatersrand rocks were concealed by younger strata. The ore bodies were found to persist to great depths and by the 1920s mining was already taking place more than 2 km below the surface. Gold production peaked at 1000 tonnes in 1970, and has since declined to a mere 200 tonnes in 2011. Nevertheless, the Basin is known to host substantial resources that may become attractive to exploit in the future, depending on the gold price and developments in technology.

The Witwatersrand Basin is filled with low-grade siliciclastic sediments. The gold is concentrated in quartz pebble conglomerates (known as reefs), is usually associated with pyrite, and locally associated with uraninite. On a micro-scale, most of the gold is associated with hydrothermal phases and occurs along micro-fractures (Muntean et al., 2005). The conglomerates are commonly interpreted to represent fluvial to fluvo-deltaic deposits on the basin edge. In most cases the conglomerate layers are only a few decimeters to several meters thick, but in a few instances the conglomerate layers are stacked on top of each other and give rise to massive ore bodies that are tens of meters thick. The conglomerate layers form sheets that extend for many kilometers along strike and dip.

4.1. Origin of the gold in the Witwatersrand Basin

The gold distribution is closely associated with sedimentary facies, and hence most exploration and mining geologists assumed that it was a placer deposit (e.g., Pretorius, 1981, 1989). It was assumed that the primary source of gold was the Archean basement rocks and greenstone belts in the hinterland of the foreland basin. However, the source of the vast amount of gold deposited in the basin (some 50,000 tonnes have been mined) has not been identified, although it is possible that the source rocks of the detrital gold have been eroded or are covered by younger strata. The existence of hydrothermal phases of gold was explained by remobilization over short distances (micrometers to meters) by hydrothermal fluids during a series of tectono-thermal events that have affected the basin (e.g., Frimmel et al., 2005). For example, Rasmussen et al. (2007) identified two metamorphic episodes. Firstly, a 2.03–2.06 Ga event, broadly contemporary with the intrusion of the Bushveld Complex, that affected...
the northwestern and central parts of the basin. The intergrowth of gold and monazite in a specimen from the West Rand goldfield at 2.045 Ga was interpreted to indicate remobilization associated with the Bushveld Complex. Secondly, a 2.12–2.14 Ga event that affected the northern and central parts of the basin.

On the other hand, several workers (e.g., Barnicoat et al., 1997; Davidson, 1965; Graton, 1930; Phillips and Myers, 1989) have argued that the gold was introduced by hydrothermal fluids sometime after the sediments were deposited. It is postulated that long-range basin-wide flow of fluids was concentrated in the conglomerates because of their greater permeability, and that gold precipitated from aqueous fluids in the presence of iron sulfides. Several possible sources and events have been postulated for the source of the gold-bearing hydrothermal fluids, for example Venterdorp-age volcanism at 2.7 Ga (Phillips et al., 1997), regional metamorphism between 2.4 and 2.0 Ga (Phillips and Myers, 1989), and the intrusion of the Bushveld Complex at ca. 2.05 Ga (Stevens et al., 1997). For example, isotope studies by Zhao et al. (2006) suggest that the source for the fluids is related to the peak metamorphism and the metamorphic fluids involved were probably derived from the basin itself, and allochthonous sulfides in the Venterdorp Contact Reef were reconstituted during fluid circulation at peak metamorphic conditions. There is no published account suggesting any direct link between the gold and, for example, deep mantle plume or subducting slab related to the gold mineralization in the basin such as those found in the other regions in the world (e.g., Lei and Zhao, 2005; Lei et al., 2009; Maruyama and Okamoto, 2007; Zhao, 2007).

This is not merely an academic debate, as the models make different predictions regarding the distribution of the ore, with significant implications for exploration strategies, the estimation of ore reserves, and mining layouts. The issue has attracted international attention. In 2005, the Society of Economic Geology (SEG) sponsored a forum where proponents of the competing modified paleoplacer and epigenetic hydrothermal models presented their views, followed by a panel discussion with audience participation. An article published in

Fig. 8. (A) Depth to the base of the Kevitsa intrusion constrained by the 3D seismic and available borehole data in the study area. Solid black lines represent near-vertical faults mapped from the seismic volume. (B) 3D visualization of the seismic data with the planned open-pit mine and the picked near-vertical faults and the base of the Kevitsa intrusion. KV322 is a borehole that intersects a series of sulfide mineralization and shows a good correlation with the reflections observed in the seismic volume (see events marked as M). Modified from Malehmir et al. (2012a).
the SEG newsletter in January 2005 provides an excellent preview of the debate (Muntean et al., 2005). Many strands of evidence must be considered to resolve the debate, ranging from micro- to meso-scale studies of the textural, geochemical and isotopic characteristics of the ore components, to macro- and mega-scale studies of the distribution of the ore bodies (Frimmel et al., 2005). Here, we demonstrate how 3D reflection seismics can be used to map the distribution and timing of meso- to mega-scale structures and provide constraints on the genetic models.

4.2. Reflection seismic mapping of the Witwatersrand Basin

The reflection seismic method was first used to explore the Witwatersrand Basin in the 1980s. Initially, 2D reconnaissance surveys were conducted to search for extensions of the basin, and blocks of ore that had either been preserved from erosion or brought to mineable depths by faulting (Pretorius et al., 1989). The first 3D survey was conducted in 1987 on the South Deep prospect (Fig. 9A, B) in the West Rand goldfield (Campbell and Crotty, 1990).

Fig. 9. (A) The location map of the West Rand and West Wits Line (Carletonville) Goldfields of the Witwatersrand Basin in South Africa (after Dankert and Hein, 2012). (B) The location of historical surveys for Kloof, South Deep, Driefontein and Western Ultra Deep Levels (WUDLs) (after Manzi et al., 2012a,b).

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mine has come into production, and boasts reserves of 29 million oz and resources of 78 million oz. Since then, 3D surveys have been widely applied in the Witwatersrand Basin for final-stage exploration, bankable feasibility studies, and mine planning (Malehmir et al., 2012b; Pretorius et al., 2003).

Four surveys conducted between 1994 and 2003 (Fig. 9B) were merged and reprocessed to obtain a seismic volume that extends approximately 40 km east–west and 16 km north–south (640 km²), with a depth extent greater than 9 km. Acquisition parameters for the 2003 surveys (the Kloof–South Deep seismic surveys covering an area of about 96 km²) is shown in Table 1. The entire seismic data cover much of the Far West Rand goldfield and part of the West Rand goldfield, covering mines and exploration lease areas owned by Anglo-gold Ashanti (Mponeng, Western Ultra-deep Levels) and Gold Fields (Kloof–Driefontein Complex (KDC); South Deep). The spatial resolution was maximized by reprocessing the data using advanced processing techniques (Manzi et al., 2012a), enabling faults with throws as small as 10 m to be mapped. The seismic data were integrated with underground mapping and exploration drilling information on the properties of the KDC and South Deep mines. The data were reinterpreted using the latest interpretation techniques in efforts to improve the mapping of geological structures (Manzi et al., 2012a) and potential conduits for methane and water (Manzi et al., 2012b).

4.3. Seismic constraints on genetic models

3D reflection seismics is able to map the present-day geometry of reflective horizons near the ore bodies, map the geometry of faults and dykes, and place constraints on the timing of fault activity and dyke intrusions. Interpretation of the Venterdsorp Contact Reef (VCR) and the Black Reef (BLR) horizons were of particular interest, and was used to provide age limits on structures. In broad terms, if the gold was introduced during the deposition of the conglomerates (the paleoplacer model), we would expect its distribution to have been controlled by syn-sedimentary faults, and have no correlation with faults that only became active following the deposition of the Witwatersrand sediments, and/or dykes that intruded thereafter. On the other hand, if the gold was introduced at a later stage (the epigenetic hydrothermal model), the gold distribution is likely to have some association with post-Witwatersrand structures or intrusions. For example, the structures may have acted as conduits through which the ore-bearing fluid was transported, or dykes may have acted as barriers that obstructed the flow of the fluids.

Dankert and Hein (2012) evaluated the structural character and tectonic history of the Witwatersrand Basin in order to test the metallogenic models. They were able to identify fold–thrust events that terminated deposition in the Witwatersrand and Transvaal basins at ca. 2.7 and 2.2–2.0 Ga, respectively. Four basin-forming events occurred in the interim, resulting in the deposition of the volcanic–sedimentary sequences of the Klipriviersberg Group, and the sedimentary sequences of the Platberg, Chuniespoort and Pretoria Groups. These basin-forming events exploited pre-existing structures such as feeder dykes, thrust faults, normal-listric faults, and growth faults. While Dankert and Hein’s analysis supports the paleoplacer model, they note that geometric, kinematic and relative chronological information was surprisingly limited.

The 3D seismic data have contributed to the understanding of the tectonic evolution of the region in several ways. The reprocessing of 1994 Leeudoorn and merging of the 1995 WUDLs surveys with the 2003 Kloof–South Deeps surveys made it possible to study regional structures on both meso-scale (meters to hundreds of meters) and mega-scale (kilometers to tens of kilometers). On a mega-scale, the seismic data resolve West Rand and Bank faults, which have maximum throws of 2 km (Fig. 10). They are north–north trending, west-dipping and listric in form (Figs. 10 and 11A). These faults displace the strata of the West Rand and Central Rand Groups (ca. 2.985–2.849 Ga) and the Ventersdorp Super-group (ca. 2.72–2.63 Ga), and form a décollement horizon in the West Rand shales. However, the faults do not displace the strata of the Paleoproterozoic Black Reef Formation and Chuniespoort and Pretoria Groups of the Transvaal Basin sequences (ca. 2.58–2.20 Ga) (Fig. 11A). Geological and seismic data suggest that both the West Rand and Bank faults experienced reactivation (folding and thrusting) during the Umzawami Event that terminated the deposition in the Witwatersrand Basin; followed by negative inversion (i.e. a change from compression to extension) where normal faulting accompanied the extrusion of the 2.71 Ga Klipriviersberg Group lavas, culminating in the deposition of Platberg Group sediments in grabens at ca. 2.70 Ga (Dankert and Hein, 2012; Manzi et al., in press). A few kilometers below the West Rand

![Fig. 10. Depth structure map of the Venterdsorp Contact Reef (VCR) derived from conventional picking across survey areas, showing the Bank and West Rand faults and the location of seismic sections shown in Fig. 11. The contour interval is 250 m.](image)
and Bank Faults, the seismic data reveal the Tandeka and Jabulani thrusts, respectively (Fig. 11A). These thrusts displace and offset the West Rand and Central Rand Groups. More importantly, the northerly-trending Libanon anticline, which happens to lie on the eastern edge of the Western Ultra Deep Levels survey and on the western edge of the Leeudoorn survey, was identified and studied in detail for the first time (Fig. 11B). The wavelength and height of the Libanon anticline are greater than 10 km and 1.5 km, respectively. The eastern limb of the Libanon Anticline is dissected by a series of west-dipping thrust-splays of the Jabulani Fault Complex (Fig. 11b). The Libanon anticline and parasitic folds have been interpreted to have formed syn- to post-deposition of the West Rand and Central Rand groups because they are folded about the hinges of the folds. The Tandeka and Jabulani thrusts displace the West Rand and Central Rand Groups and thus also formed after them. These structural features provide important new constraints on tectonic styles and the timing of tectonic events (Manzi et al., in press). The seismic data cube was also used to compute isopach maps, and to map faults and dykes on a mega-scale. This information was used to determine the relative rates of deposition, the extent of unconformities, and the relative ages of fault activity and dyke intrusion, and the orientation and ratio of principal stresses.

Advanced signal processing techniques were used to improve spatial resolution and to map faults and dykes in plan and section on a meso-scale (meters to hundreds of meters). Edge detection techniques, in particular, were used to map fault throws as small as 10 m.

Fig. 11. (A) Seismic section (amplitude display) across the West Rand and Bank faults, showing the Jabulani and Tandeka thrusts at about 1.2 km below the Bank Fault and West Rand Fault, respectively. (B) Seismic section (amplitude display) across the major Libanon anticline at the merge boundary of the 1995 WUDLs and 2003 Kloof seismic survey. WUDLs: Western Ultra Deep Levels; WRG: West Rand Group; CRG: Central Rand Group; VCR: Ventersdorp Contact Reef. Note sharp change in the amplitudes is due to different datasets that were merged together.

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These features were correlated with known intersections of water and gas, and structures that likely acted as present-day fluid pathways were identified (Manzi et al., 2012b; Fig. 12A, B). This type of information can also be used to test genetic models. For example, Meier et al. (2009) mapped and geochemically analyzed numerous mafic dykes that cut and displaced gold reefs on a mine in the Klerksdorp goldfield. The geochemical data indicated that the dykes are the feeders of the Klipriviersberg Group flood basalts that immediately overlie the Witwatersrand rocks, while mapping indicated that they were emplaced into active or pre-existing faults. Meier et al. (2009) concluded that the dykes would have acted as barriers to regional-scale movement of fluids within the major gold-bearing conglomerate horizon in the region (the Vaal Reef), and that basin-scale gold enrichment must have occurred during sedimentation or early diagenesis. While no similar geochemical study has been conducted in the area covered by our data, the projection of dykes and faults into the VCR horizon (Fig. 13A, B) provides a ready model of barriers to fluid transport. The notion of basin-scale fluid movement caused by later tectonic or thermal events can now be tested.

5. Seismic investigations at the Brunswick No. 6 base metal and associated iron deposits

The Bathurst Mining Camp (BMC), northern New Brunswick, Canada, is a major base-metal producing region that contains the super giant Brunswick No. 12 VHMS deposit and several Zn–Pb–Cu deposits within a sub-circular area 50 km in diameter (McCutcheon, 1992). The search for additional base metal deposits in the camp requires an efficient exploration strategy based on a good understanding of the highly deformed and complex geology, combined with modern geophysical tools to provide drilling targets and to improve the understanding of the geological framework at depth. Within this context, 2D and 3D seismic surveys were acquired in two key prospecting areas of the BMC. Seismic data previously acquired by industry in the Halfmile Lake area led to the discovery of an about 6 Mt VHMS lens located at a depth of 1.2 km (Malehmir and Bellefluer, 2009; Matthews, 2002). Here, we review the main characteristics of seismic data acquired in a second area of the BMC located over the Brunswick No. 6 mine (Fig. 14). The Brunswick No. 6 deposit is located approximately 27 km southwest of the city of Bathurst in northeast New Brunswick, Canada (Fig. 14). By 1982, Brunswick No. 6 had produced about 12.2 Mt of 5.43% Zn, 2.15 wt.% Pb, 0.40 wt.% Cu, and 67 g/t Ag (Luff, 1995). Seismic reflection data (2D and 3D) were acquired in the late 1990s and early 2000s by industry to explore for new deep-seated deposits along the prospective Brunswick horizon. Re-processing and re-analysis of the data show that the Brunswick horizon occurs within a reflective package that extends down to at least 6–7 km depth (Cheraghi et al., 2011, 2012; Malehmir and Bellefluer, 2010). In addition, the seismic data provide some indications of the presence of BMC rocks beneath the Carboniferous sedimentary rocks exposed at surface east of the mining area and deeper reflections previously associated with a mafic/ultramafic dominated ophiolitic slab underlying the BMC. These results clearly demonstrate the utility of seismic reflection methods in complex mining environments.

5.1. Geological background

The BMC is composed of several tectonic blocks and slivers that were juxtaposed during the closure of the Tetagouche-Exploits back-arc basin (van Staal et al., 2003). Fig. 15 shows a schematic cartoon of tectonic framework of the Brunswick complex in the late Ordovician–early Silurian (450–440 Ma). According to van Staal (1994), the Cambro-Ordovician clastic metasedimentary sequence of the Miramichi Group is the oldest rock in the BMC. The Brunswick complex formed during a continent–continent collision in the late Ordovician and Early Silurian. Prior to the collision, a series of oceanic–continental obductions in the early Ordovician and before that trapped large blocks of oceanic rocks (mainly ophiolite) underneath the volcanic and sedimentary rocks of the Miramichi Group (Figs. 14 and 15). The Tetagouche Group hosts the VHMS and iron deposits and is a primary target for deep exploration in the BMC. The oldest part of the Tetagouche Group is the Nepisiguit Falls Formation, which contains felsic volcanic and volcanoclastic rocks. Younger rocks of the Flat Landing Brook Formation contain rhylitic flows and rhyolitic volcanic/hoalclastic rocks. The alkali basalt flows of the Little River Formation are the youngest part of the Tetagouche Group. The Brunswick horizon is observed in the upper part of the Nepisiguit Falls Formation and includes a mixture of sulfide, carbonate, oxide, and silicate facies. This horizon is a key target for geophysical and geochemical exploration in the camp (Gross and McLeod, 1980).

Thrusting and folding observed at surface suggest several repetitions of the geological units in the BMC (van Staal, 1987). In the study area, an example of such repetition is shown in a geological cross-section provided by Willis et al. (2006). The cross-section suggests tight and small folding structures down to deep level in the crust (Fig. 16; see A–A’ in Fig. 14 for location of the cross-section). Since the Brunswick horizon hosts most base metal deposits in this camp, it is important to image its spatial distribution and any possible repetition as detailed recognition of this prospective structure at depth could lead to new discoveries in the area.
5.2. Seismic constraints

The available infrastructures, mining facilities, and a need to explore for new deposits at greater depths were the incentives to acquire 2D and 3D seismic data in the Brunswick area. In the late 1990s and early 2000s, Noranda Inc. (now Xstrata) acquired three 2D seismic profiles and a 3D seismic survey (Table 1) in the Brunswick No. 6 area (see Fig. 14). Details on the acquisition parameters and re-processing of the data can be found in Cheraghi et al. (2011) and (2012), Malehmir and Bellefluer (2010). Noranda Inc. and the Geological Survey of Canada also acquired wireline-logging data in a few boreholes near Brunswick No. 6 to help with the interpretation of the seismic data. The petrophysical logs showed that both the Brunswick horizon and gabbro have high acoustic impedances that contrast with the generally low acoustic impedance of the host rocks. As a result, both units produce reflections that can be observed in seismic images. In contrast, rocks of the Miramichi Group are mostly transparent to seismic waves and can help indirectly to determine the location of the reflective formations (Cheraghi et al., 2011; Malehmir and Bellefluer, 2010).

Fig. 17 shows re-processed data for the profile BRN991001 that extends 6 km from west to east just south of the Brunswick No. 6 mine (see Fig. 14). The data quality is generally good with many reflections that almost reach the surface and allow correlation with surface geological map to help the interpretation. Reflections all dip to the west in alternation with noticeable transparent sequences. A comparison between surface geological observations and shallow reflections suggests that reflective zones P1 and P2 are generated from gabbro and alkali basalts of the Little River Formation in contact with the felsic volcanic rocks of the Nepisiguit Falls Formation, and the Brunswick horizon. The P1 and P2 reflection packages are imaged down to approximately 4–5 km depth. The high amplitude reflection in P1 (see arrows in Fig. 14) is interpreted to be generated by the Brunswick horizon (Cheraghi et al., 2011; Malehmir and Bellefluer, 2010). This reflection, although clearly visible, could be hard to distinguish from gabbro reflections without the support of geological information. However, the entire reflection package can be used to guide exploration. The reflection package P2 does not reach the surface, but its projection intersects the surface at the location of the Nepisiguit Falls Formation east of the profile. Rock units of the Flat Landing
Brook Formation and Miramichi Group show, in general, very weak reflectivity. The short and high amplitude reflections (R1–R4) appear to be generated by relatively thin gabbroic dykes. The correlation with gabbro dykes observed at surface is particularly convincing for R1 and R2. The discontinuous reflections at 2.25 s are interpreted as a possible repetition of BMC rocks thrust beneath the one exposed at surface. If correct, this interpretation suggests that the BMC could extend further than expected to east, and may underlie the Carboniferous sedimentary rocks exposed at surface. A short sub-horizontal reflection at approximately 2.75 s marks a change in the structural style that could indicate the lower limit of the Brunswick belt (at approximately 8 km). We associate this reflection with the mafic/ultramafic dominated ophiolitic slab possibly underlying the BMC.

When compared with the 2D profile, the 3D seismic data present lower resolution seismic image, which is mostly related to the acquisition geometry used during the survey (Cheraghi et al., 2012). However, the 3D data contain most of the elements observed on the 2D profile (Fig. 17). Fig. 18 shows a subset of the 3D volume with the P1 and P2 reflection packages. The deeper reflection observed at approximately 2.25 s (or about 6–6.5 km depth) on the 2D profile is also clear on the 3D data (Fig. 18). The attitudes of the reflections on the 3D data in the southern part of the 3D are consistent with an eastward thrusting of the BMC rocks.
Careful analysis of 2D and 3D seismic data, correlation of processing results with the surface geological map, and some borehole petrophysical measurements help to define the architecture of the subsurface formations in the Brunswick No. 6 area. In particular, the prospective Brunswick horizon is shown to occur within a reflection package that is imaged using the seismic data. Interpretation of deeper reflections also suggests a possible repetition of the BMC rocks at greater depths, which could also extend underneath the Carboniferous sedimentary rocks east of the mining camp. Results presented in this section of the paper demonstrate the utility of seismic methods in complex and highly deformed mining camps.

6. Conclusions

In this article, we have reviewed and presented reflection seismic data from three major mining areas of the world in order to provide information about structural and lithological relationships with mineralization. As is evident, performance and character of seismic data depend on the site conditions and geological complexities. While reflections from geological structures are often continuous and coherent in the Witwatersrand Basin, reflections are shorter and less continuous in the Brunswick No. 6 area and in Kevitsa. Nevertheless, combined with the available geological observations, seismic data from these regions...
provide crucial information about the overall architecture of the upper crustal structures that could be useful for future deep exploration.

Seismic data from the Kevitsa area were used to define the 3D geometry of the ore-bearing Kevitsa intrusion and the surrounding geological units, thus providing a framework for future exploration in the area. Moreover, the Kevitsa deposit is located within a part of the intrusion that is associated with distinct reflectivity of a similar spatial constraint. We believe that this reflectivity is dominantly associated with a zone of magmatic layering that controls the bulk of the economic mineralization. Thus, the seismic data can be used to delineate a near-mine exploration envelope. In particular, the reflective zone continues below the known mineralization, thus indicating continuation of the mineralization at depth. Additionally, the seismic data revealed a wealth of structures crosscutting the Kevitsa deposit and the intrusion as whole. The structures inferred from the 3D data can be critical for geotechnical planning of the mine.

Fig. 17. Stacked section along the BRN991001 profile, showing a series of westward, steeply dipping reflections imaged down to about 1.7 s (i.e., about 5 km depth). Reflectivity pattern shows a sequence of reflective and transparent package repeating from the east to the west. The Brunswick horizon and associated structures appear within the reflective package P1. See text for interpretation of P1, P2, R1, R2, R3 and R4. See Cheraghi et al. (2011) for more details about the projected cross-section onto the profile.

Fig. 18. 3D views from the seismic volume. (A) Unmigrated stack volume showing the depth extent of the Brunswick horizon (P1 and P2) and a high amplitude reflection (I1) interpreted to mark the base of the Brunswick volcano–sedimentary belt. (B) Migrated stacked volume and correlation of a strong high amplitude reflection with the geological model of the Brunswick horizon. A portion of the seismic cube for a time slice at 500 ms. See Fig. 14 for the surface projection of the cube and text for interpretation of events marked as P1, P2, and I1. Figure is modified from Cheraghi et al. (2012).
the Brunswick horizon that is consistently imaged within a reflective package that extends down to about 7–8 km depth. A sequence of reflective and transparent zones observed from the data would very likely represent a series of thrust faults implying a repetition of major lithological units including BRN horizon. Future studies should aim at linking these rather shallow but high-resolution seismic data from the upper crust with deeper structures and provide further insights about the overall structures of the crust and upper mantle in these highly mineralized regions. Until such data are available, these reflection seismic data serve a basis for our understanding of the major geological structures associated with the mineralization.

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