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# Tectonic and Metallogenic Implications of Regional Seismic Profiles in the Timmins Mining Camp

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## Abstract

Four regional seismic reflection profiles totalling 153 line km were acquired near Timmins, Ontario, within the southern Abitibi greenstone belt. Five additional high-resolution lines targeted specific metallogenically important features such as the Porcupine-Destor deformation zone. Interpretation of these profiles individually and in a composite north-south transect reveals a number of prominent bands of reflectors within the upper 15 km of the crust that define a series of folds or antiformal stacks of thrust nappes. Structures and stratigraphy mapped at the surface confirm structural culminations in these locations. At depths greater than 10 km the reflectors have generally shallower dips implying broad folding. Major ore deposits such as those at the Kidd Creek, Hollinger, McIntyre, and Dome mines are located on the northern, steeply dipping limbs of these antiformal stacks, implying that the fold structures focused post tectonic mineralizing fluids within the upper crust into the near surface. The Porcupine-Destor deformation zone is proximal to the large gold deposits near Timmins and is revealed by the new seismic data to be a composite of early fold structures and late transpressive fault arrays.

## Introduction

THE MAIN PURPOSE of this seismic survey was to image regional stratigraphy, major structures, and lithology of the southern Abitibi greenstone belt, an area of special interest to gold and base metal explorers. The overall intent was to provide guidelines for finding such deposits, particularly within the same stratigraphic or structural setting along strike from many of the known ore deposits mined in this area and especially beneath areas of glacial (clay and till) cover. Previous reflection seismic profiles in the region acquired by LITHOPROBE (Green et al., 1990; Jackson et al., 1995; Verpaelst et al., 1995) demonstrated the potential for this type of surveying to develop an understanding of shallow as well as deep crustal structure in these Archean crystalline rocks.

The seismic sections and interpretative comments given here are not intended to provide comprehensive synthesis of all survey lines or exhaustive individual descriptions; rather, we emphasize reflections associated with the relatively well established regional stratigraphy, a few prominent structures and their possible significance. The enhanced understanding of the three-dimensional regional stratigraphy provides an improved context for local geochemical or geophysical anomalies and known orebodies. The full crustal structure and comparisons with earlier deep reflection profiles in the Abitibi and other Archean domains both in Canada and worldwide will be addressed more fully elsewhere.

## Regional Setting

The Abitibi greenstone belt (MERQ-OGS, 1983; Ludden et al., 1986; Jackson and Fyon, 1991; Corfu, 1993) is the largest preserved greenstone belt in the world, trending generally east-west across the southern Superior craton. In the east, it is truncated by the ca. 1 Ga Grenville Front tectonic zone, whereas in the west, the Abitibi belt proper is truncated by a major Paleoproterozoic intracratonic thrust, the Kapuskasing zone. The latter exposes a gently west dipping oblique crustal section that displays three megalayers, each about 10 km thick (see Percival and West, 1994, and references therein). Supracrustal rocks, deposited mainly between 2750 and 2700 Ma and metamorphosed to greenschist facies, are characterized by mafic compositions, upright structural features, and weak reflectivity. The base of the greenstone belt at 10 to 12 km is intruded by tonalitic gneiss that crystallized at 2710 to 2660 Ma and was metamorphosed to amphibolite facies by 2645 Ma. Reflectivity increases with depth into layered gneiss that crystallized at 2760 to 2620 Ma and was metamorphosed to amphibolite and granulite facies at 2700 to 2600 Ma. The gneiss lithologic units include anorthosite, tonalite, mafic gneiss, and paragneiss that are layered on a 0.1- to 10-km scale and characterized by low dips and bright reflectivity. Farther west, within the Kapuskasing

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zone, at high structural levels within the dipping crustal section and approximately along strike, the continuation of the Abitibi greenstone belt reappears in the Wawa subprovince. Hence, the Abitibi greenstone belt is merely a remnant from an originally much larger Neoarchean granite-greenstone terrane that records rapid crustal growth in the Neoarchean (e.g., Card, 1990; Percival et al., 2004).

The area is a typical Late Archean granite-greenstone terrane, characterized by polycyclic volcanic stratigraphy, overlain by a late-stage sequence of turbiditic sedimentary rocks and finally synorogenic clastic rocks (Fig. 1). These rocks were intruded by numerous granitoid plutons and deformed by several phases of folding and faulting. Isotopically, the volcanic rocks are largely juvenile (e.g., Corfu and Noble, 1992;

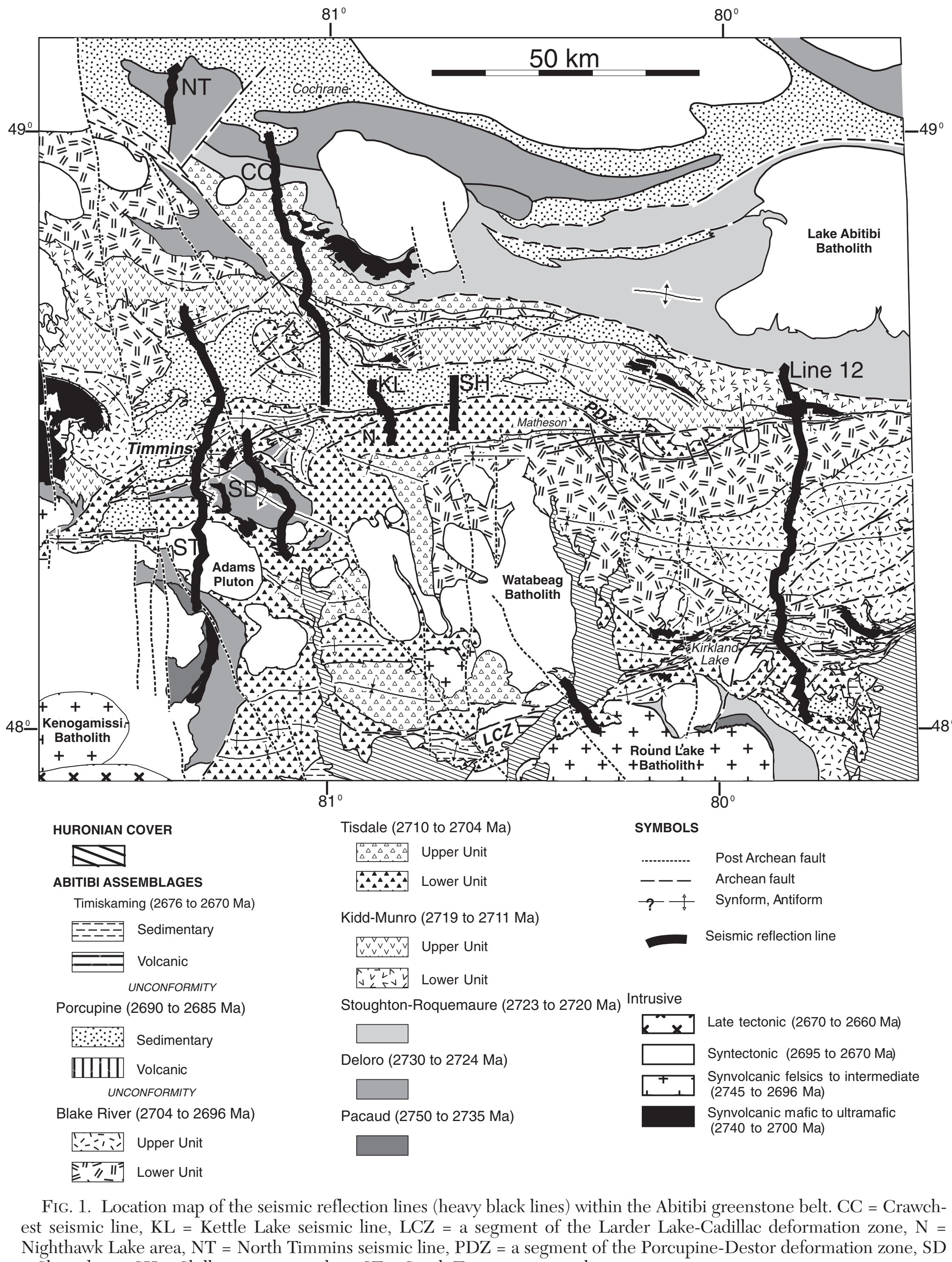



FIG. 1. Location map of the seismic reflection lines (heavy black lines) within the Abitibi greenstone belt. CC = Crawchest seismic line, KL = Kettle Lake seismic line, LCZ = a segment of the Larder Lake-Cadillac deformation zone, N = Nighthawk Lake area, NT = North Timmins seismic line, PDZ = a segment of the Porcupine-Destor deformation zone, SD = Shaw dome, SH = Shillington seismic line, ST = South Timmins seismic line.

Ayer et al., 2002), although there are rare and subtle traces of the involvement of ca. 2.8 to 2.9 Ga basement (e.g., Barrie and Davis, 1990; Ayer et al., 2005b). Examples of this basement are exposed in the nearby Kapuskasing zone (Moser et al., 1996) and to the north of the Abitibi in the Opatica gneiss belt (e.g., Davis et al., 1995).

The regional stratigraphy of the southern Abitibi greenstone belt in this part of Ontario is relatively well known and constrained by numerous absolute radiometric ages (Ayer et al., 2002, 2005a, b). Seven of the main assemblages mapped regionally are of relevance to the seismic survey area (Fig. 1). The 2750 to 2735 Ma Pacaud, 2730 to 2724 Ma Deloro, 2723 to 2720 Ma Stoughton-Roquemaure, 2719 to 2710 Ma Kidd-Munro, 2710 to 2704 Ma Tisdale, and 2703 to 2696 Ma Blake River assemblages are largely composed of mafic volcanic rocks, commonly pillowed, with minor ultramafic and intermediate to felsic volcanic units. These assemblages are unconformably overlain by the 2690 to 2685 Ma Porcupine and 2676 to 2670 Ma Timiskaming assemblages, which are predominantly sedimentary units representing detritus derived from the older volcanic units in the form of turbidites, conglomerates, and sandstones that generally are more felsic than the volcanic substrate.

Plutonic rocks in the region form three groups: synvolvanic, syntectonic, and late tectonic (Ayer et al., 2005b, and references therein). Detailed geochronology demonstrates that some intrusive complexes (e.g., the Kenogamissi and Round Lake batholiths, Fig. 1) formed over 90 m.y. by multiple intrusive events. Synvolcanic intrusions range in age from 2745 to 2696 Ma and are coeval with the main volcanic sequences and predate significant compressional strain. Syntectonic intrusions (e.g., the Adams pluton, Fig. 1), as dated between 2695 to 2685 Ma, are coeval with the Porcupine assemblages and with some of the major deformation episodes in the region and therefore occur in the cores of folds. Late tectonic intrusions formed between 2670 and 2660 Ma, typically as massive batholiths.

The deformation history is complex and varies within the study area and, therefore, is grossly simplified here. See Ayer et al. (2005b, and reference therein) for a more complete description. The oldest structures recognized regionally are north-south–trending folds such as the one cored by the Kenogamissi batholith (Fig. 1); these folds represent $D_1$ deformation at 2696 to 2690 Ma that predates deposition of the Porcupine assemblage. East-west–trending folds and local south-over-north thrusts represent a $D_2$ phase that forms interference patterns with $D_1$ folds. This $D_2$ deformation postdates Porcupine assemblage deposition but predates Timiskaming deposition and therefore occurred from 2695 to 2676 Ma; large-scale $D_2$ folds represent the most readily recognized deformation in the area. Three deformation phases postdate Timiskaming assemblage deposition and are mostly recognized as transpressional strains associated with the Porcupine-Destor zone (PDZ, Fig. 1). The earliest of these, $D_3$, relates to left-lateral displacement in the Porcupine-Destor zone and to gold mineralization between 2671 and 2673 Ma (Ayer et al., 2005b).

The Porcupine-Destor zone is characterized by a fault trace over 400 km long with generally steep structures in outcrop. Few systematic differences in metamorphic grade occur across the deformation zone in broadly similar rock assemblages. Synclinally infolded panels of the Timiskaming assemblage are truncated by this zone and thus require that some deformation was late. No pluton is known to stitch the Porcupine-Destor zone. Gold mineralization is concentrated along minor faults, especially in S-shaped bends within the main zone. Kinematic information is conflicting (also see Benn and Peschler 2005); overall it suggests left-lateral $D_3$ strain followed by right-lateral $D_4$ strain.

## Methodology: Seismic Data Acquisition and Processing

Crustal-scale seismic reflection profiles were acquired using the Vibroseis® technique, in the Timmins area, as part of the multidisciplinary Discover Abitibi Project (Ayer et al., 2005b; Reed et al., 2005). The two-dimensional survey lines were oriented north-south across major geologic trends; from the northern edge of the Abitibi greenstone belt, 82 km north of Timmins, to volcanic rocks and granites located 30 km south of Timmins (Fig. 1). Parallel lines were located from the city of Timmins in the west, to the hamlet of Shillington 48.5 km to the east, and across the major structural zone of the Porcupine-Destor deformation zone at four locations (Fig. 1). Major gold deposits, including historic producers and current mines, occur along the Porcupine-Destor zone and subsidiary structures. A single line, 30 km west of Kirkland Lake (Fig. 1), crosses the Larder Lake-Cadillac deformation zone, a zone similar to the Porcupine-Destor zone, where it is unconformably overlain by Proterozoic sedimentary rock of the Huronian Supergroup. One line passed near the giant Kidd Creek deposit in the Kidd-Munro assemblage to assess whether any seismic signature could be associated with the known geometry of a major volcanogenic massive sulfide (VMS) deposit.

This seismic survey was reconnaissance in nature; the nearest existing seismic lines are the LITHOPROBE Kapaskasing survey located 100 km to the west and the LITHOPROBE Abitibi survey line 12 located 90 km to the east of Timmins (Fig. 1). The Kapuskasing survey targeted the west-dipping midcrust of the Abitibi greenstone belt (Percival and West, 1994), whereas LITHOPROBE line 12 crossed the central part of the greenstone belt (Green et al., 1990). The Discover Abitibi survey described in this paper used the duel regional and high-resolution modes in order to provide a state-of-the-art LITHOPROBE-style transect across the Abitibi greenstone belt, applying techniques with the highest spatial resolution possible across structures key to mineral deposits.

The deep seismic reflection profiles were acquired in June and July 2004 by Kinetex Inc. of Calgary, using two modes indicated in the Appendix. Four lines, with a total length of 153 line km, were surveyed in a regional mode with geophones spaced every 25 m, vibrator points every 50 m, and a source frequency sweep of 10 to 96 Hz. Five lines, with a total length of 51 km, were surveyed in a high-resolution mode with geophones spaced every 12.5 m, vibrator points every 25 m, and a source frequency sweep of 10 to 160 Hz. Prominent reflections appear in the 140- to 160-Hz bandpass on the stacked sections analyzed for frequency content.

Survey lines were located along available roads (mostly gravel) that crossed desired geologic targets. Seismic source arrays consisted of one, two, or three vibrators. Single vibrators were used in areas with concerns about surface damage (e.g., in parks and areas of ground collapse near mines in Timmins). Generally, the high-resolution lines employed two vibrators, whereas the regional lines used three vibrators. Single three-component geophones were used: one component oriented vertically and two horizontally, as north-south and east-west components. The processed sections that are shown here used only the vertical component. Horizontal components will be processed and analyzed in future studies.

Processing by Sensor Geophysical Ltd. of Calgary was completed in March 2005. The vertical-component Vibroseis field records were diversity stacked and correlated for 6 s on the high-resolution lines and for 12 s on the regional lines. Rough estimates typically assume average rock velocities of 6,000 m/s, therefore maximum depths resolved on the sections are approximately 18 and 36 km, respectively. Overburden-bedrock interfaces at a few hundred meters depths are resolved on most sections. Strong crustal reflections are seen from 0.5 (less than 1,500 m) to as much as 7 s (about 21 km). Some sections show bedrock responses as shallow as 0.2 s (less than 600 m), although these shallower responses are generally weaker. Final stacked sections involved processing using several types of static corrections, dip move out (DMO), migration, and several stages of bandpass filtering (App.).

Laboratory measurements of density and seismic wave speeds within representative samples indicate a bimodal grouping into volcanic and sedimentary rock types that is useful for seismic interpretations of these rocks (Salisbury et al., 2000, 2003; Reed et al., 2005). In other words, the highest amplitude reflections would be expected where rocks from the first group of largely mafic-ultramafic volcanic Abitibi assemblages are in contact with plutonic or sedimentary rocks from the second group or are intruded into and thus interlayered with felsic-intermediate volcanic rocks. These statements apply to relatively pristine rock types; if metasomatized, the velocities and densities will be homogenized and thus much less reflective.

## Structural Interpretation of Seismic Sections

Regional profiles were designed to help constrain the relatively large scale geologic framework of the Timmins mining camp and possibly to map crustal-scale pathways of mineralizing fluids, as has been documented in Australia (Drummond et al., 1998). Seismic data were therefore recorded for a sufficient period of time to produce 12-s sections, equivalent to 35- to 40-km depth. From earlier LITHOPROBE surveys in the Abitibi greenstone belt, the Moho, or the base of the crust, is expected at 9- to 11-s two-way travel time (e.g., Calvert and Ludden, 1999). The emphasis for this survey, however, was on reflectors located in the uppermost 15 km of the crust. Many of these represent either supracrustal strata within the Abitibi greenstone belt stratigraphy (Ayer et al., 2002) or structures within the underlying gneissic basement which are probably upper crustal shear zones (e.g., Green et al., 1990; Jackson et al., 1995; Percival et al., 2004). The knowledge of the underlying structures revealed by the seismic data portrayed here greatly improves the understanding of large-scale folds and deformation zones mapped at the surface and near surface in mines.

Throughout this paper the term reflector is used to designate a rock layer with properties suitable for reflecting seismic P waves with wavelengths between 60 to 600 m. The term reflection refers to the seismic wave that appears as wiggles on a seismic section. Solid lines are used in figures to highlight prominent or laterally continuous reflections that are interpreted to represent laterally continuous reflectors. Dashed lines indicate interpreted faults defined by truncations of laterally continuous reflectors. In places a reflector may appear to coincide with an inferred fault because this reflector truncates other reflectors. Whether these truncations should be interpreted as an unconformity, a thrust, or a normal fault depends on the specific stratigraphic context.

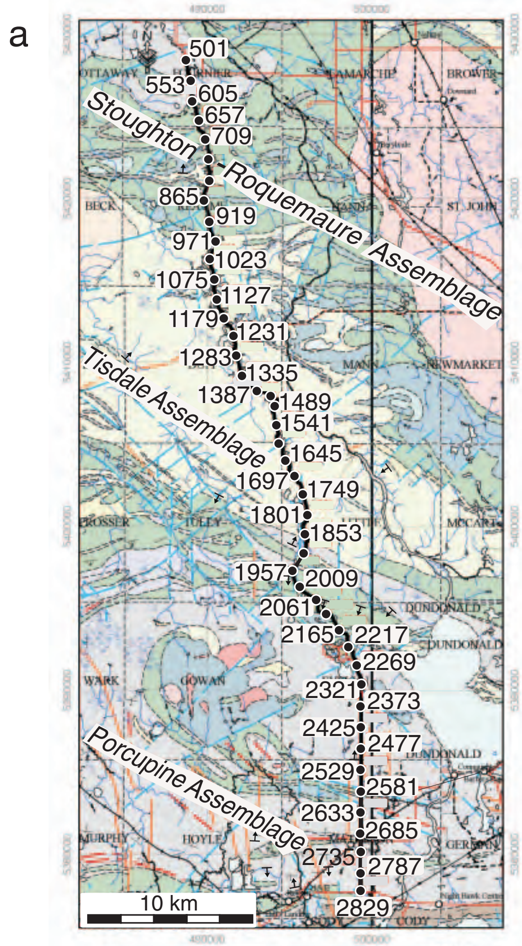
At the northern end of the Crawchest line (discussed below) and on the North Timmins line (NT, Fig. 1), laterally continuous reflections occur down to 10.2-s two-way travel time but are rare at greater depths. Farther south, the decrease in reflectivity with depth is more gradual. This pattern is similar to that observed on other Abitibi seismic reflection profiles and was previously related to a crustal underplate of relatively homogeneous mafic rocks (Calvert and Ludden, 1999). The results from the northernmost parts of the survey indicate that 12-s records were sufficient to image the entire crust of the Abitibi belt and that Moho occurs at about 35-km depth.

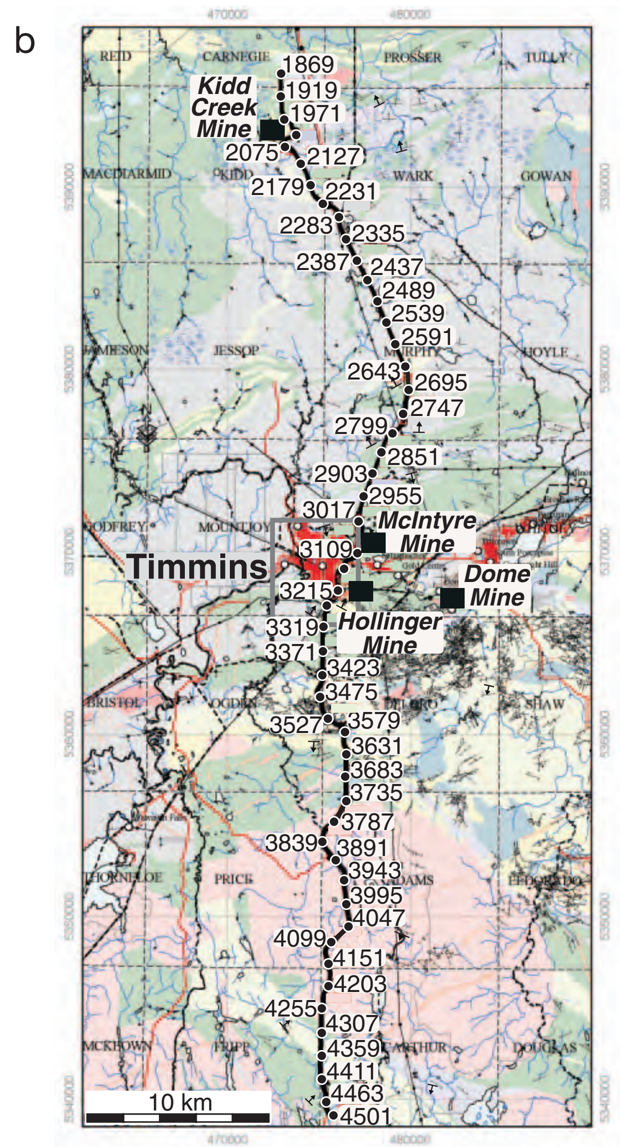
The interpretation of two-dimensional seismic data in a region of known three-dimensional structure that includes complex and interfering fold patterns must be considered as permissive but not definitive. For example, where two sets of reflections appear to intersect or cut off one another, the rock strata acting as reflectors may indeed intersect across a fault surface or the intersection may be apparent because reflections from structures to one side of the profiling line are slightly different than those from the other side of the profile due to folding or deformation in the direction perpendicular to the profile.

### *North Timmins-Crawchest line*

Logistical considerations (primarily permission to work on provincial highways) required this profile to be collected in two segments (Figs. 1, 2a). The northern end is located near Cochrane and the southern end west of the Kettle Lakes Provincial Park. The intent was to investigate the regional architecture of the volcanic assemblage along the northern margin of the Abitibi greenstone belt at depth. Although the profile did not cross the mapped northern margin, prominent reflections at 2.5 s (about 8-km depth) at the northern end of the Crawchest line and at 2.0 s on the North Timmins line are interpreted to represent the approximate base of the Abitibi greenstone belt, as represented by the basal volcanic units of the Deloro and/or Pacaud assemblages (bg, Fig. 3; Ayer et al., 2002).

Farther south, near VP 1100, these reflections appear to splay at about 6-km depth, above and below a wedge of less-reflective crust (w, Fig. 3). This geometry suggests a thrust duplex structure, typically associated with horizontal shortening or terrane accretion (e.g., Boyer and Elliot, 1982) and a style of deformation that appears to be characteristic of the rest of this crustal section, as well as the others in the southern Superior region (e.g., Calvert and Ludden, 1999). Throughout the section, laterally continuous reflections intersect or truncate one another at angles of 10° to 45°, a pattern



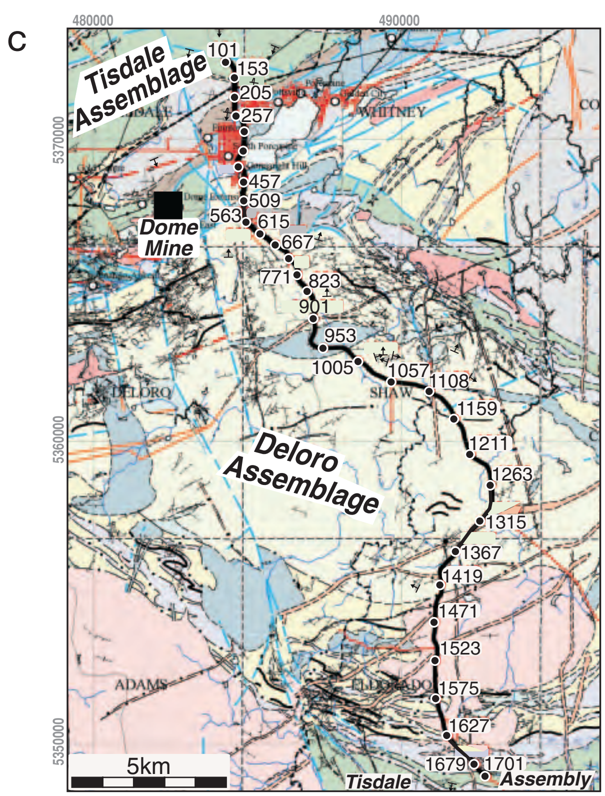




FIG. 2. a. Geologic strip map along the Crawchest line, showing reference vibration points (VPs) along the seismic survey route and measured structural attitudes at nearby outcrops. b. Geologic strip map along the South Timmins line. c. Geologic strip map along the South Porcupine line. Geology after Ayer et al. (2005a).

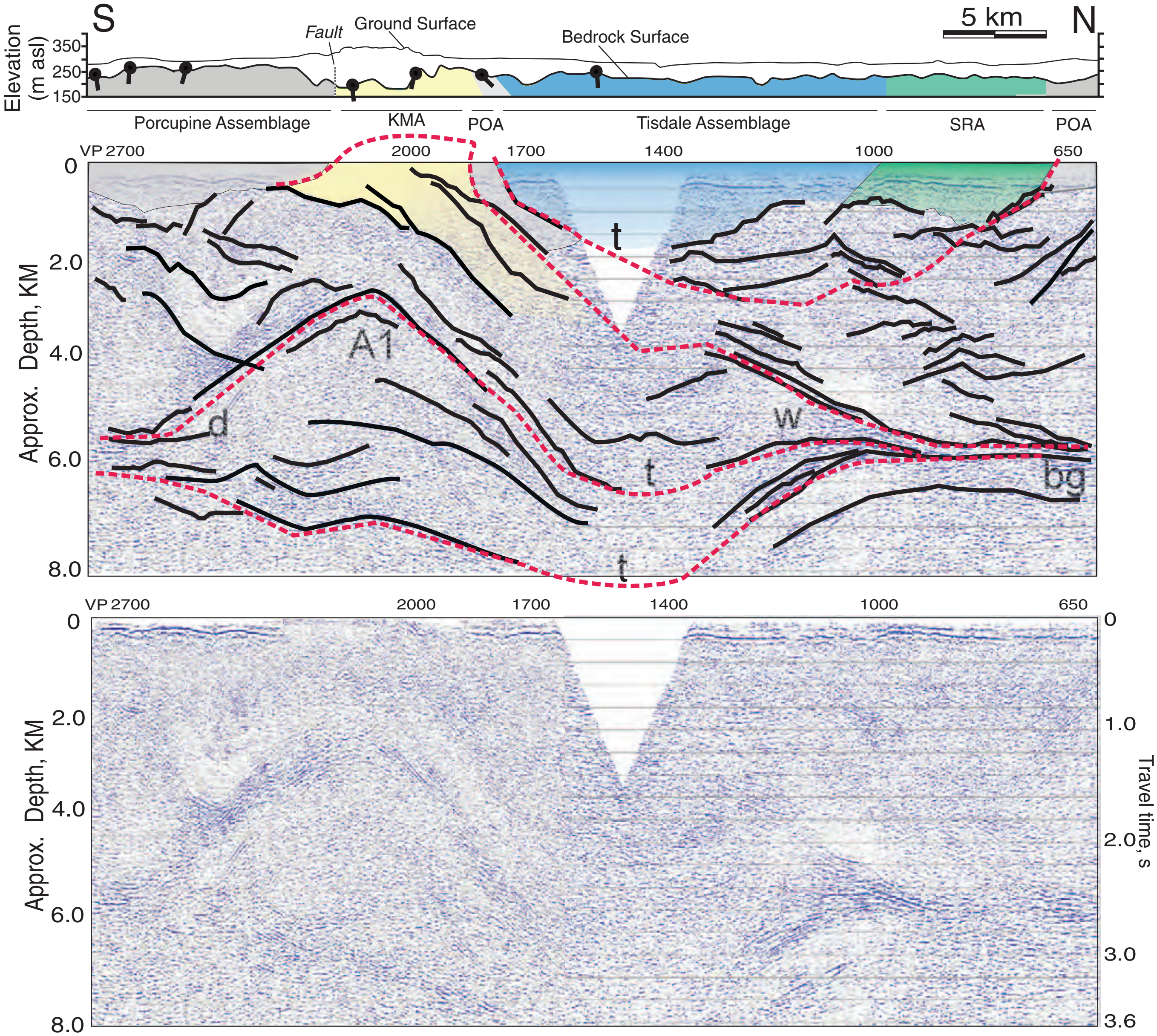



FIG. 3. Reflection profile section of the Crawchest line (bottom) and its interpretation (top). The bar at the top indicates the rock units and observed attitudes of strata as projected onto the seismic line. KMA = Kidd-Munro assemblage, POA = Porcupine assemblage, SRA = Stoughton-Roquemaure assemblage. The "notch" in the center of the seismic data is where no source points were possible due to lack of access for the vibrators. Solid lines in the interpreted section highlight prominent or laterally continuous reflections; dashed red lines are inferred faults. Color-coded polygons represent rock assemblages as defined in Figure 7. Letters refer to features discussed in the text. The line marked "bedrock surface" is approximate as it is based on increases in velocities determined by refraction static corrections that may be affected by many factors.

typical of thrust or reverse faulting. At VPs 2150 to 2500, a prominent reflective band at 3 to 5 km (1–1.8 s) defines a broad antiform fold (A1, Fig. 3). This antiform structure correlates well with the distribution of assemblages at the surface because it directly underlies the Kidd-Munro assemblage, an older part of the volcanic stratigraphy, which is flanked by younger volcanic and sedimentary assemblages to the north and south (Figs. 1, 3). At 6- to 9-km depths (2.5–3.5 s), a prominent north-dipping band of reflections merges with the south limb of the antiform to define another example of classic thrust duplex geometry in cross section (d, Fig. 3). The folding was possibly enhanced by late intrusion of a seismically homogeneous pluton within the core of antiform A1.

Between the splay and fold (i.e., VP 1100–2000) lies a section of weaker, almost uniformly north-dipping reflections beneath an area of Tisdale assemblage rocks. This metavolcanic sequence could be as much as 6 to 8 km thick but appears to be repeated once or twice by thrust faults (t, Fig. 3), one of which reaches the surface and thrusts Tisdale assemblage rocks on top of Porcupine assemblage metasedimentary rocks near VP 1870. Two more of these possible thrust faults (Fig. 3) coincide with the prominent reflections discussed above and thus potentially bound thrust sheets of metamorphic or plutonic crystalline rock as well as greenstone strata.

*South Timmins line*

This regional line begins north of the Kidd Creek base metal mine, passes through the Hollinger and McIntyre gold mine sites and ends 30 km south of Timmins on the Pine Street extension, south of the Adams pluton (Figs. 1, 2b). The intent of this line was to provide a crustal-scale perspective on structures and potential mineralizing fluid pathways related to some of the largest gold and copper-zinc deposits in Canada.

Weak north-dipping reflections appear in the uppermost 1 s (3 km) near the Kidd Creek mine site (VP 2040). A strong reflection sequence occurs at 3.5 s two-way travel time (S1, Fig. 4). To the south at VP 2440, two or three prominent reflective bands define an antiform structure (A1, Fig. 4) at 1.2 to 2.0 s (3- to 6-km depths). This connects northward to

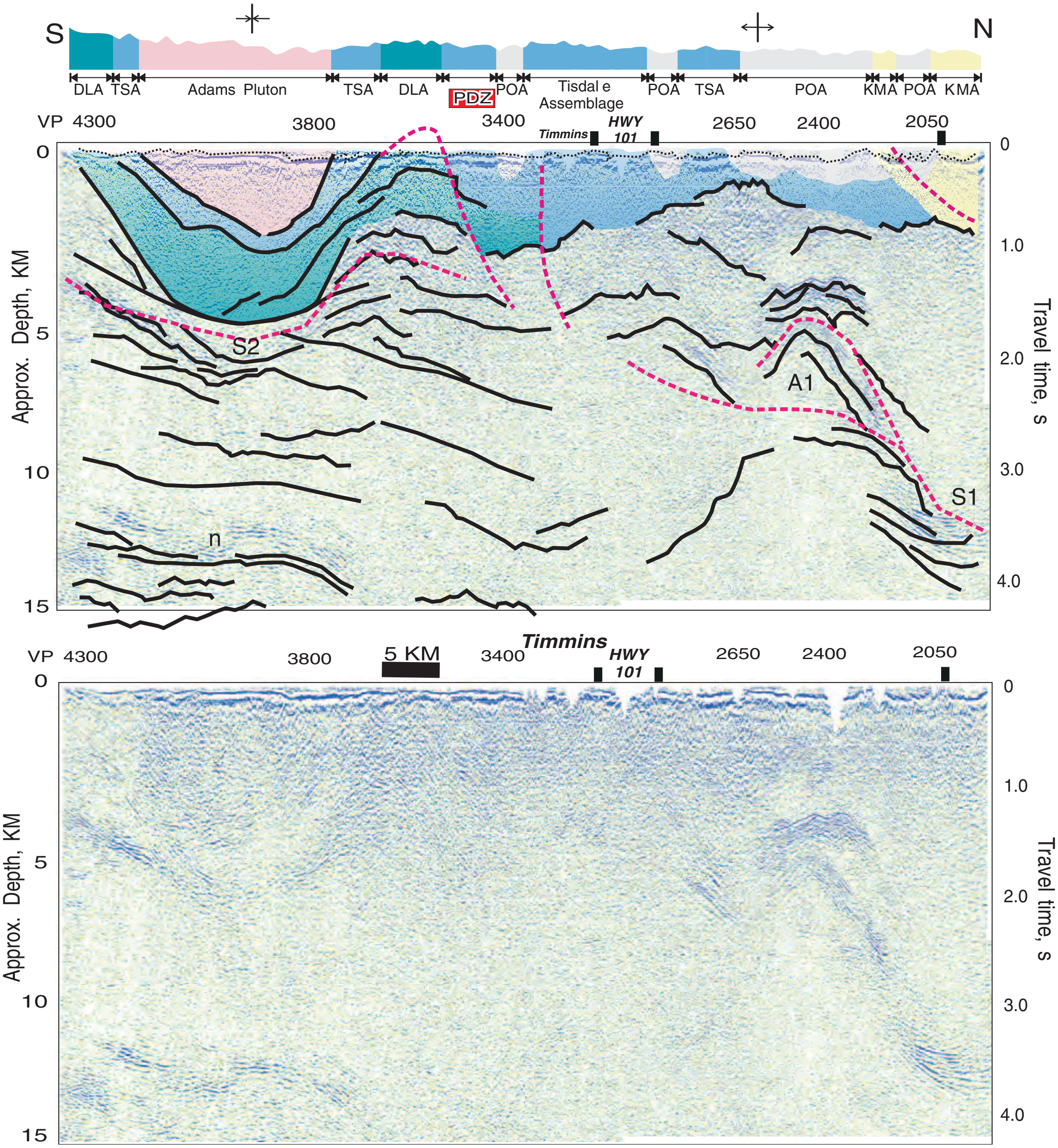



FIG. 4. Reflection profile section of the South Timmins line (bottom) and its interpretation (top). Symbols as in Figure 3. DLA = Deloro assemblage, TSA = Tisdale assemblage. Black rectangles represent major gold or base metal mines located on or near the survey route. PDZ = Porcupine-Destor deformation zone. The dotted line at the top of the interpreted section is the inferred base of glacial cover or weather zoned.

reflection S1 and southward with a synformal reflection to form a pattern (A1) similar to that observed on the Crawchest regional line, again suggesting duplex thrust structures or associated folding throughout the upper crust. Folded Tisdale and Porcupine assemblage volcanic and sedimentary rocks, respectively, directly overlie this part of the section at the surface. Farther south and at the same inferred stratigraphic level, only weak reflections occur beneath the Hollinger-McIntyre gold mines (VPs 2900–3300) and thus imply alteration of the seismic properties of these strata.

This profile crosses the Porcupine-Destor deformation zone near VP 3430 but shows little, if any, direct evidence in the seismic data. Weak, semicontinuous, mostly north-dipping reflections characterize this crust (VPs 3380–3600) at 1.0 to 3.5 s. From VPs 3500 and 3700 tightly folded units of the Deloro assemblage are overlain by the Tisdale assemblage at the surface (Fig. 1) in an area where reflections indicate broad, open folds in the uppermost 3 km.

Farther south, between VPs 3744 and 4310, the profile traverses the Adam's pluton. This area is underlain by a prominent, broadly synformal reflection sequence at 1.0 to 2.0 s (3–6 km; S2, Fig. 4) and suggests that the pluton is a shallow, sill-shaped body, possibly filling the hinge of a broad synformal fold. This fold may be the westward continuation of the syncline centered within the upper part of the Tisdale assemblage southeast of the pluton (Fig. 1). Foliation within the pluton is generally south dipping where observed, but Deloro assemblage strata along the southern margin of the pluton dip northward and are thus consistent with the deeper reflections at 3 to 6 km and other prominent and more shallowly dipping reflections at 12 to 15 km (n, Fig. 4).

Within the upper-crustal part of this profile (3–4 s two-way travel time) numerous reflections are observed in the north and the south but generally less so in the center of the section (VPs 2800–3600, Fig. 4). This part of the section coincides with the crustal block immediately north of the surface trace of the Porcupine-Destor deformation zone and extensive gold mineralization near the surface (Figs. 1, 2b).

*Shaw dome line*

This regional line starts just north of Highway 101, in the town of South Porcupine, passes along the west shore of Porcupine Lake and continues southward through the Shaw and Eldorado townships, across the Redstone River, to end southwest of Nighthawk Lake (Figs. 1, 2c). The purpose of the line was to image crustal structures near the Dome mine and beneath the Deloro assemblage rocks within a prominent regional-scale anticline identified as the "Shaw dome." The northernmost 7 km were collected using high-resolution parameters, processed independently, and then merged with the regional line (Fig. 5).

Nearly the entire line (VPs 450–1400) displays a prominent band of reflections between 0.4 to 1.5 s (1- to 5-km depth) that dip outward from an apex at about VP 900. Although reflections are weak in the uppermost kilometer, this prominent band largely correlates with the observed dome structure indicated by stratigraphy and a broad fold structure at the surface (Figs. 1, 2c, 5). This band of reflections is underlain (to about 2.2 s) by a relatively reflection poor zone, which is in turn underlain by another prominent band of shallowly south dipping reflections at 2.0 to 2.6 s (6- to 8-km depth; S, Fig. 5).

Between VP 1435 and 1560 the profile crosses the Eldorado Tonalite where shallowly southward dipping reflections between VPs 1400 and 1600 at 0.4 to 0.8 s (e, Fig. 5) suggest that this sill-like intrusion is less than 1.5 km thick and was intruded into the Tisdale assemblage rocks above the south-dipping Deloro assemblage strata on the south flank of the Shaw dome structure. Several steeply south dipping reflections within the uppermost 1 s, that cross the shallow-dipping reflections may also be seismic energy scattered off of a number of near-vertical, diabase dikes that obliquely intersect the profile at VPs 1325, 1460, and 1500 (Figs. 2c, 5). Some of these suspect reflections are concordant with deeper antiformal reflections; some are steeper and straighter and thus more typical of scattered energy.

The outward-dipping reflections at 2- to 3-km depths project to the surface as rocks of the Deloro assemblage (Ayer et al., 2002). The deeper band of inward- or south-dipping reflections might represent Pacaud assemblage strata at the base of the Abitibi supracrustal sequence or a shear zone within crystalline rocks. The former possibility is suggested by the presence of inherited Pacaud age zircons in Tisdale volcanic units on the southeastern margin of the dome (Ayer et al., 2005b). The lens of less reflective crust at 3- to 7-km depth is typical of homogeneous rocks such as those found in granitic plutons. The presence of a granitic pluton here is consistent with lower densities inferred from gravity measurements in this area (Reed, 2005a, b).

The truncation of south-dipping reflections along a north-dipping line between depths of 2 and 8 km at the southern end of this profile (f, Fig. 5) is interpreted as a north-dipping fault. If the fault follows the curvature of the Shaw dome, it would permit a mapped lens of Deloro assemblage strata (Fig. 1) to have been structurally emplaced within the Tisdale assemblage on the southeastern margin of the dome (Figs. 1, 5; Ayer et al., 2005b). In this interpretation, a fault on the northern, outward-dipping contact of the lens of Deloro assemblage strata is characterized by normal, dip-slip displacement. Normal displacement is consistent with apparent offset of the floor of the pluton.

At the northern end of this profile, where the high-resolution section was merged with the regional line, the prominent reflection band at 2- to 3-km depths is reduced in amplitude near VP 550 but continues to dip northward to near the end of the profile (n, Fig. 5). The northward continuation of this reflection band underlies the surface trace of the Porcupine-Destor deformation zone and indicates that the fault zone cannot dip to the south at this location.

This and the other high-resolution lines were designed to target specific structures that possibly control the pathways of mineralizing fluids or the eventual location of orebodies such as those associated with the Porcupine-Destor zone. Acquisition parameters were guided by previous seismic surveys in Canada and Sweden that targeted orebodies or fault zones (Perron et al., 1997; Bergman et al., 2002). Near South Porcupine, the target structure was the Porcupine-Destor deformation zone (PDZ, Fig. 6a). The 10-km length of the high-resolution lines makes them unsuitable for regional correlations, but structures associated with this major, regional fault zone were clearly imaged.

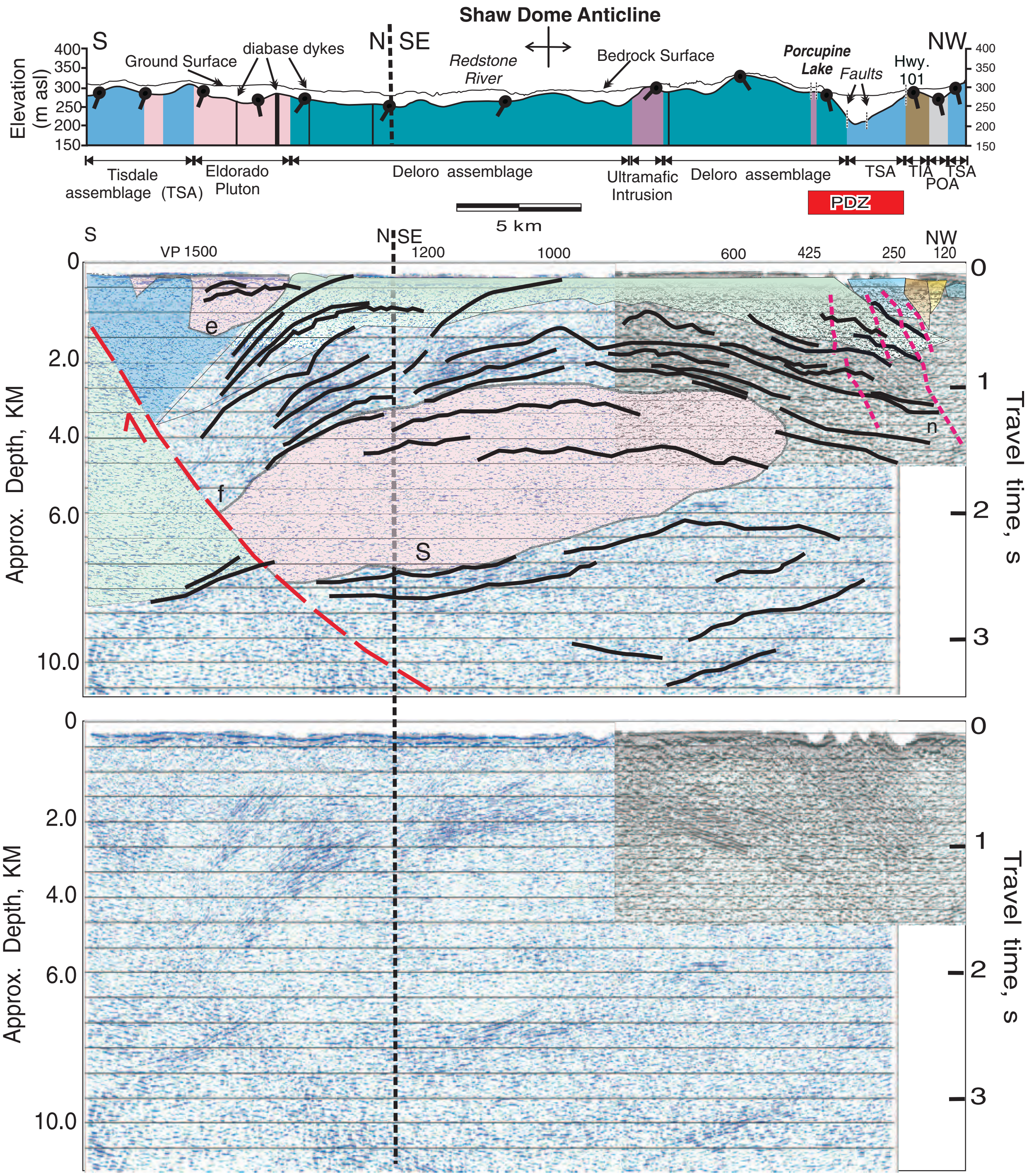



FIG. 5. Reflection profile section of the South Porcupine line. Shaw dome section (bottom) and its interpretation (top). Vertical dashed line at VP 1250 marks a major change in the direction of the line. Other symbols as in Figure 3. TIA = Timiskaming assemblage. VPs 101 to 430 are the South Porcupine high-resolution seismic section superimposed on the regional line section, not displayed at a higher density. PDZ = Porcupine-Destor deformation zone. Prominent reflections across this entire section clearly define an anticline or dome structure in the upper 5 km of the crust. The part of the section immediately below crops out of the Eldorado Tonalite. VPs 1400–1500 are also nonreflective down to projected Deloro assemblage rocks but do indicate that the Eldorado Tonalite is a sill or "pancake"-shaped bysmalith.

The southern half of the high-resolution South Porcupine section (VPs > 425) contains mafic volcanic rocks of the Deloro assemblage that dip gently northward toward the Porcupine-Destor deformation zone from the center of the Shaw dome structure down to 1.2-s two-way travel time (~3-km depth). A number of parasitic anticlinal folds appear in the uppermost 0.3 s of this section (e.g., VP 560, 0.1 s). Between VPs 230 and 540, nearly vertical zones disrupt the generally

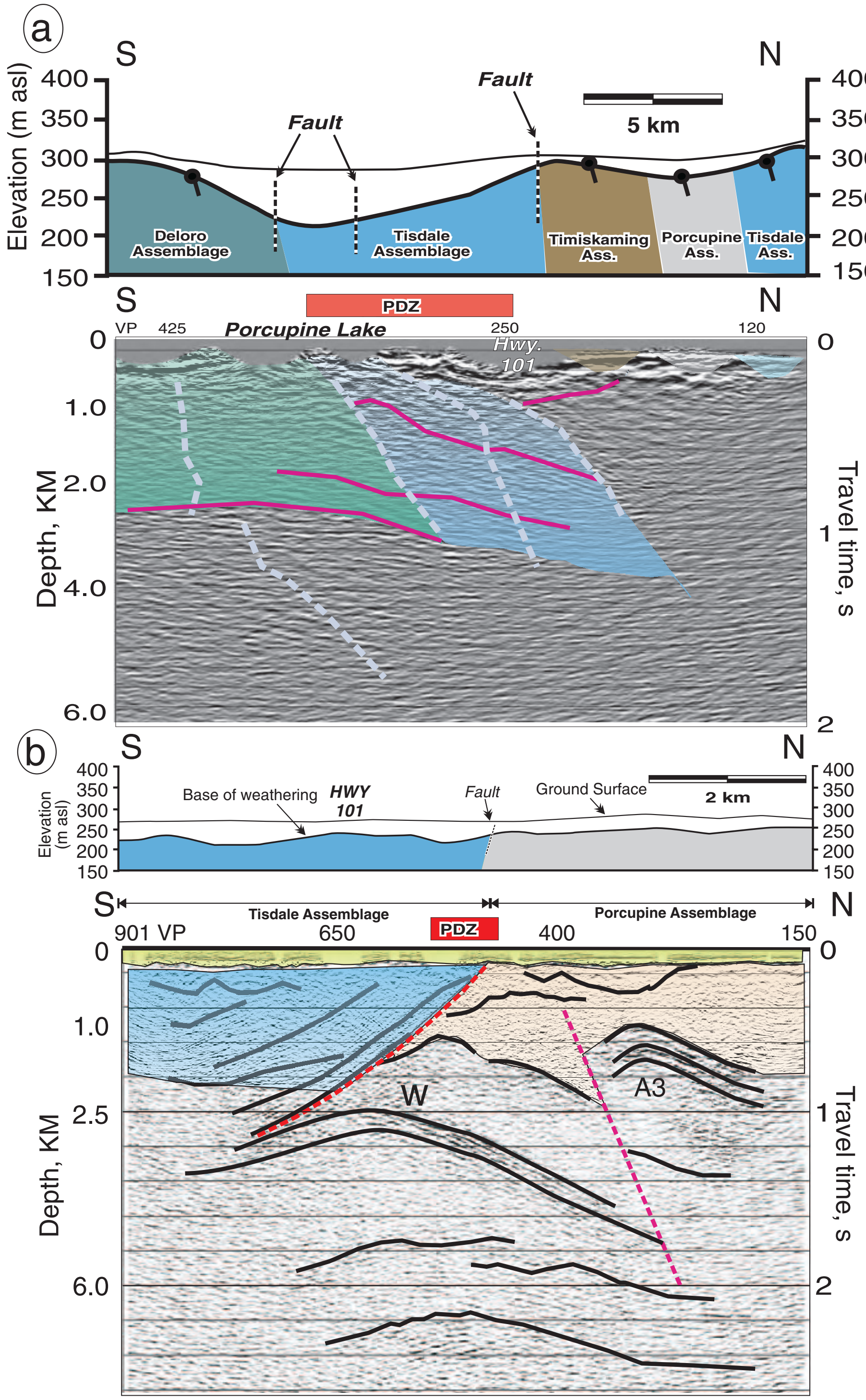



FIG. 6. High-resolution profiles for (a) South Porcupine section shown as part of Figure 5, but here shown in a grayscale format. Continuous reflections dip gently northward beneath the entire Porcupine-Destor deformation zone (PDZ) from outcrops of Deloro assemblage rocks and thus suggest that the fault zone must dip northward. Small offsets or truncations of some of these reflections may define a network of steeply north dipping fractures over a zone 20 km wide that represents the fault zone here. The steeply dipping rocks of the Tisdale, Porcupine, and Timiskaming assemblages which crop out north of the Porcupine-Destor zone have no discernible associated reflectivity. (b). Shillington profile. PDZ = Porcupine-Destor deformation zone. About 150 m of clay or till overburden is defined by the light green color and closely spaced, near-horizontal reflectors across the entire top of the section. Prominent reflectors define anticlines at 1- to 3-km depths on both sides of the Porcupine-Destor zone. Reconstructing these prominent reflectors suggests that one fault dips steeply northward from ~VP410 and is a reverse fault. Listric, south-dipping reflections in the upper 2.5 km of the northern third of the section probably represent Tisdale assemblage rocks; the deepest of these reflections projects to the surface trace of the Porcupine-Destor zone.

weak, north-dipping reflections in several locations; these vertical zones coincide with faults mapped at the surface, including the Porcupine-Destor zone. These zones may represent subsidiary splays of the main fault that appears to dip very steeply (~70°) to the north below its surface location (adjacent to Highway 101). North of the Porcupine-Destor zone, the lack of reflections in the uppermost 0.2 s suggests that the steeply dipping Timiskaming, Porcupine, and Tisdale assemblage rocks are not imaged by the seismic data as processed here.

### *Shillington*

The Shillington high-resolution line is the survey's easternmost crossing of the Porcupine-Destor zone, located about 50 km east of Timmins and 80 km west of LITHOPROBE line 12 (Fig. 1). The mapped trace of the Porcupine-Destor zone intersects the profile near VP 500 and separates Tisdale assemblage rocks to the south from Porcupine assemblage rocks to the north (Fig. 6b). The Tisdale assemblage rocks are imaged through a thin layer of overburden as parallel southward-dipping reflections everywhere south of the Porcupine-Destor zone; the northernmost reflections in this set marking the southern margin of the Porcupine-Destor zone (Fig. 6b). At about 1.0 s these reflections are deflected into a northward-dipping group of reflections (VPs 380, 1.75 s; 640, 1.0 s) to define a wedge-shaped structure (w, Fig. 6b). This and other deflected reflectors suggest that here the shallow Porcupine-Destor zone is a thrust dipping moderately to the south.

The most prominent feature occurs at VP 200 to 300, 0.5 to 0.7 s where high-amplitude reflections, representing Tisdale assemblage rocks underlying Porcupine assemblage rocks, define an antiform fold structure (A3, Fig. 6b). This feature appears to be offset vertically from the northward-dipping reflections described above; implying a reverse fault dipping steeply to the north. This fault projects to the surface at VP 420, north of the Porcupine-Destor zone. It may be a subsidary fault related to later movements in the Porcupine-Destor zone (Bleeker, 1995; Bateman et al., 2005, 2008) but with an opposing dip and sense of displacement.

The north-south Kettle Lakes line is also centered on the Porcupine-Destor zone and Highway 101 and passes through the Kettle Lakes Provincial Park about 30 km east of Timmins (Fig. 1). Kettle lakes occur in glacial till deposits and this area is thought to have 100 to 200 m of glacial sand on top of clay that covers basement here and farther to the east. Over 0.2 s of subhorizontal reflections at the top of the section mark this thicker layer of overburden. Sand can attenuate high-frequency seismic wave energy and this section looks like a lower frequency version of the Shillington seismic section. This section thus supports the along-strike continuity of structures associated with the Porcupine-Destor zone.

## Discussion

### *Upper crust folds*

The new regional seismic reflection profiles have provided valuable insights into the large-scale geologic structural patterns within the upper crust of the northern part of the Abitibi greenstone belt near the Timmins mining camp, the Porcupine-Destor deformation zone, and the surrounding area. The seismic profiles show regions of lateral continuity of reflective strata and shear zones rather than vertically aligned reflector truncations (Fig. 7), emphasizing folds and low-angle thrust faults rather than steep faults. Many observed

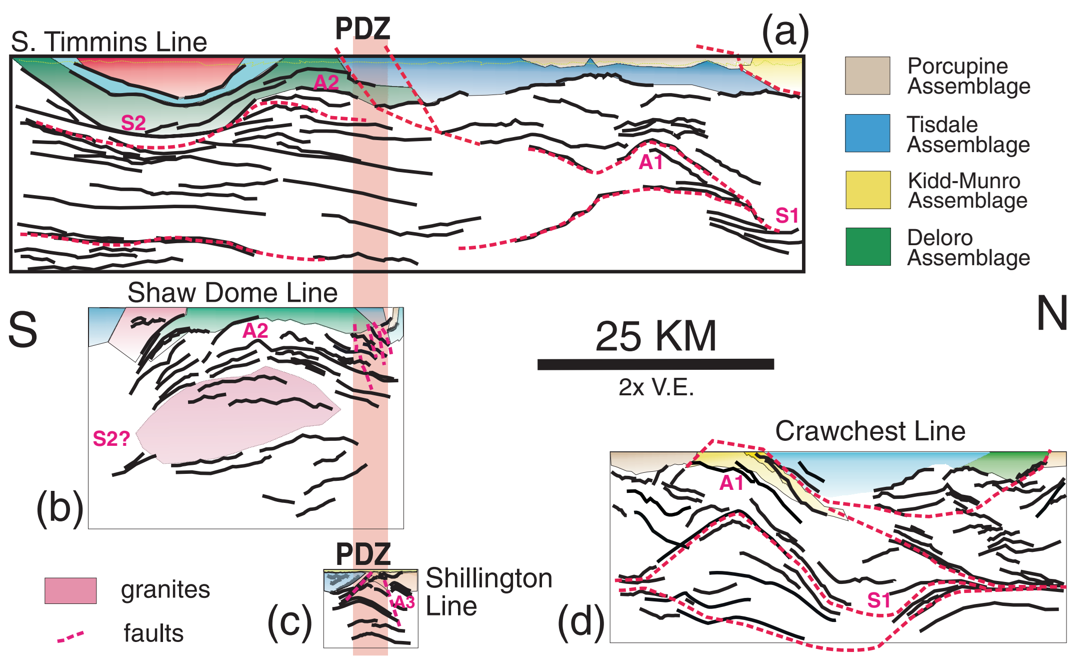



FIG. 7. Composite of all north-south seismic sections illustrated in Figures 3, 4, 5, and 6. All sections are at the same vertical and horizontal scales with 2× vertical exaggeration. Sections are aligned laterally by matching like structural culminations (A1–A3) marked by outcrops of deepest greenstone stratigraphy (Deloro or Kidd-Munro assemblage rocks). PDZ = Porcupine-Destor deformation zone. Labels (A and S) refer to synforms and antiformal thrust stack structures discussed in the text.

reflector geometries are similar in parallel profiles up to 50 km apart, and in most cases are consistent with structures mapped at the surface. Overall, the reflector geometries are typical of the classic thrust nappes or stacks observed in the Swiss Alps, Canadian Rockies, or young orogens where significant horizontal shortening of the crust has occurred (e.g., Boyer and Elliot, 1982). Here contractional deformation is inferred to have occurred at 2695 to 2665 Ma (Ayer et al., 2005b).

A composite north-south regional structural cross section of the upper crust contains numerous broad, open folds in a series of antiforms and synforms (Fig. 7). Three of the antiforms are of particular interest. The first occurs at the southern end of the Crawchest line (Figs. 3, 7d) and northern part of the Timmins line (Figs. 4, 7a) where Kidd-Munro assemblage rocks crop out and have apparent thrust fault contacts with Tisdale and possibly Porcupine assemblage rocks (A1, Fig. 7). On the Crawchest line (Fig. 7d) this structural culmination is directly underlain by several interpreted nappes, at least two of which contain Abitibi greenstone strata and form an antiformal thrust stack. On the South Timmins line (Fig. 7a) a similar stack is observed but is offset to the south by about 15 km. The Kidd Creek mine is located 10 km above the northern flank of this deep structural culmination but within tightly folded strata near the southern contact between Kidd-Munro assemblage and Porcupine assemblage rocks.

The second antiform is the Shaw dome and its shallower version near the center of the Timmins line (VP 3600, Fig. 4; A2, Fig. 7). Here Deloro assemblage rocks crop out with outward-facing stratal dips directly above consistently outward-dipping seismic reflections in both profiles. The Shaw dome anticline appears to have been broadened and amplified by intrusion of a granitic body at 3- to 7-km depths. The anticline on the Timmins line (Ogden and Deloro townships) is a more open fold that is underlain by an interpreted thrust and, at 6- to 16-km depths, by uniformly north-dipping reflectors.

The third antiform is coincident with the Porcupine-Destor deformation zone and appears best defined in the Shillington and South Porcupine high-resolution sections (A3, Fig. 7c) but also on the Kettle Lakes and Timmins lines (Fig. 1). This is a much smaller antiform that occurs primarily within Tisdale assemblage strata and is offset by steeply dipping faults (Fig. 6). This antiform, together with a relatively shallow south dipping thrust and steep north dipping faults, appears to collectively form the structural break called the Porcupine-Destor deformation zone that has been traced over 400 km along strike. The composite feature thus described here is consistent with characteristics of the fault zone observed and modeled along strike (Benn and Peschler 2005) in that a faulted fold is observed but not necessarily a detachment fold.

The folds and antiformal stacks of thrust sheets appear to be the primary structural feature of the Abitibi greenstone belt in the Timmins region. Individual antiforms or thrust faults inferred from the reflection geometries are consistent with mapped structures at the surface. This structural style appears to continue to, and beyond, the base of the supracrustal greenstones and into gneissic rocks of the mid-crust. The gneissic rocks representing either “restite” from the melting event that generated the granites or young granitic melts ejected into former oceanic crust. Many major mineralization zones occur above the steepest limbs of the regional-scale anticline structures.

Steep-limbed anticlines and thrust stacks are more pronounced in the north, whereas south of the Porcupine-Destor zone the reflectors are generally shallower dipping (Fig. 7). This southern pattern is more similar to the style of the broad synformal reflectors underlying the Blake River assemblage on LITHOPROBE line 12 (Fig. 1; Jackson et al., 1995; Hajnal et al., 2006). This change in pattern indicates that more shortening has been accommodated by the northern part of the belt. This also explains why a relatively undisturbed autochthonous stratigraphic succession is preserved in the area between the Porcupine-Destor and Larder Lake-Cadillac deformation zones (Fig. 1), whereas north of the Porcupine-Destor zone, the stratigraphy has been complicated by a collage of folded and thrust, intercalated older volcanic and synorogenic sedimentary assemblages (Ayer et al., 2002, 2005b).

### *Full crust structure*

The overall structural style throughout the crust is similar to that observed on the LITHOPROBE Abitibi transect to the east (Calvert and Ludden, 1999) and the western Superior transect (White et al., 2003). The Abitibi transect is generally characterized by dominantly north dipping reflectors in the mid- to lower crust that have been related to underthrusting of the Abitibi terrane by the Pontiac terrane from the south (Calvert and Ludden, 1999; Benn, 2006). The upper crust in the vicinity of the Porcupine-Destor zone, as imaged by LITHOPROBE line 12 (Fig. 1), contains little coherent structure but has hints of reflectors dipping both north and south. It is thus potentially consistent with the upper crustal structure described here for the Timmins area. On the southern half of the western Superior transect, the broad, open folds in the upper crust of the Wabigoon subprovince are underlain by dominantly north dipping reflectors associated with the underthrust Wawa or Minnesota River Valley terrane that, in turn, is inferred to be underlain by underthrust oceanic crust (White et al., 2003).

### *Porcupine-Destor zone and gold mineralization*

Assessments of the economic implications of these seismic data indicate a number of significant features. The first is the association of gold deposits with the Porcupine-Destor deformation zone and the nature and orientation of component faults. It has long been known that numerous gold deposits occur near this fault and associated higher order structures in the Timmins gold camp (Robert and Poulsen, 2001).

Evidence for the Porcupine-Destor zone is not clear in the South Timmins profile (Figs. 4, 7a). Inversions of gravity and magnetic data indicate that the fault dips steeply to the north in this area (Reed, 2005a, b). These inversions have indicated fault geometry within the upper 4 to 5 km of the crust but have not been extended to suggest the depth of the base of the greenstone belt. An economically significant feature of the part of the South Timmins profile north of the Porcupine-Destor zone is the possible overall attenuation of upper crustal reflection amplitudes beneath the Hollinger and McIntyre mines. These two mines represent a world-class gold deposit that produced over 30 million ounces (Moz). If the upper crust in this area experienced a significant alteration event which attenuated reflectivity, then this type of observation has value as an exploration tool for identifying alteration associated with similar types of deposits elsewhere.

The high-resolution portion of the South Porcupine profile is located about 3 km east of the Dome mine, another world-class deposit which has produced over 15 Moz of gold and is closely associated with the Dome fault, a subsidiary structure occurring about 1.5 km north of the Porcupine-Destor zone. The seismic data in this profile provide evidence (Figs. 5, 6) for a series of north-dipping parallel faults that are most likely correlated with the Porcupine-Destor zone and parallel structures such as the Dome fault.

A number of possibilities exist to explain the change in the orientation of the Porcupine-Destor zone from a series of north-dipping faults west of Nighthawk Lake (N, Fig. 1) to a moderately south dipping fault zone, east of the lake. Reorientation by later folding is the preferred explanation, but a steep, isoclinal fold (Peschler et al., 2004; Benn and Peschler, 2005) is a viable explanation. Numerous folding events have affected the stratigraphy and structures in the Timmins camp but are not evident in the Shillington segment of the Porcupine-Destor zone (Fig. 1). The south-dipping fault zone near Shillington may represent an early thrust fault, whereas the steep north dipping structures, such as the reverse fault evident in the Shillington profile north of the Porcupine-Destor zone, occurred later in the structural evolution of the area. These features may have implications for the lack of gold deposits along the Nighthawk-Shillington segment of the Porcupine-Destor zone. Instead, the more economically significant structure is the Nighthawk Lake deformation zone, an auriferous fault which splays southwest of the Porcupine-Destor zone, west of the Shillington line (N, Fig. 1).

Farther east, surface expressions of the Porcupine-Destor zone continue to dip moderately southeastward into Hislop Township (near Matheson, Fig. 1) where the Porcupine-Destor zone has a southeasterly strike and dips moderately southwest at 45º to 60º (Berger, 2002). Farther to the east, the Porcupine-Destor zone strikes east-west and dips steeply south at 80º to 85º near the Holloway mine (Ropcahn et al., 2002). A southerly dip is also evident at greater crustal depths in the LITHOPROBE seismic profile (line 12) in this vicinity (Jackson et al., 1995).

### Comparisons with the Eastern Goldfields of Australia

Another area within an Archean craton that has benefited from a program of seismic reflection profiling that focused on the better understanding of gold mineralization processes is the Eastern Goldfields province in the Yilgarn craton of Western Australia. Between 1991 and 2001, seismic reflection data were acquired along a 213-km-long line (Goleby et al., 1993; Swager et al., 1997), a series of shorter lines forming a grid in the Kalgoorlie area (Goleby et al., 2000, 2002; Owen et al., 2001), and a line in the northern Yilgarn (Goleby et al., 2004).

One of the outstanding results of the initial 1991 work in the Yilgarn was the identification of a detachment fault at the base of the supracrustal volcanic-sedimentary sequence (Swager et al., 1997). It lies at a depth of 4 to 7 km, deepening eastward, and truncates folds and faults in the supracrustal rocks. Only the gold-barren Ida fault extends the full depth of the crust, implying that the detachment is a relatively late structure, truncating all other faults and postdating gold mineralization, and that the last movement in the Ida fault is younger still. Below the detachment fault, in the felsic middle crust, are high-amplitude, subhorizontal reflectors. The detachment is not as well marked in the northern Yilgarn profiles, although the crust is divided into three structurally distinct horizons and the best mineralized belts are marked by faults that penetrate the entire crust (Goleby et al., 2004). In the work reported here, and that farther east in the Abitibi (Verpaelst et al., 1995; Calvert and Ludden, 1999), no comparable basal structure can be recognized so that the Abitibi compares most favorably with the northern Yilgarn.

Crustal-scale shear zones are deemed by some a necessary condition for the formation of gold deposits such as those in the Eastern Goldfields and Abitibi provinces (Goldfarb et al., 2001; Goleby et al., 2004). In the northern Yilgarn survey (Goleby et al., 2004), the important gold-bearing structures such as the Laverton tectonic zone are crust-penetrating structures. Near Timmins, the Porcupine-Destor deformation zone is indistinctly imaged or cannot be clearly traced below a few kilometers (e.g., Fig. 6b). The composite LITHOPROBE Abitibi transect section (Calvert and Ludden, 1999) suggests that neither the Porcupine-Destor nor the Cadillac-Larder Lake deformation zones penetrate the full crust. This suggestion is supported by observations in the nearby Kapuskasing zone, where Moser et al. (1996) demonstrated that the subhorizontal structures in the mid- to lower crust formed after ca. 2660 Ma, probably later than and truncating the steep faults at higher structural levels. Near Kalgoorlie, the detachment possibly deformed crust-penetrating shear zones, terminating them at the base of the upper crust. Crust-penetrating shears may also have been exaggerated in their importance or only shear zones restricted to the upper crust are most important for the very biggest mine camps such as Timmins-Porcupine and Kalgoorlie.

Both provinces are characterized by antiformal structures that fold earlier formed thrust stacks, a result of the transpressional deformation identified in both greenstone belts. $D_1$ or early-$D_2$ thrusts were folded in late-$D_2$ in the Eastern Goldfields, and all these structures are cut off at the detachment. The Kalgoorlie gold camp lies on the crest of one of these antiformal stacks (Goleby et al., 2002). Similarly, $D_1$ folds were refolded during $D_2$ deformation in the Timmins camp. In the latter case, the interference fold patterns and subsidiary two-dimensional antiforms extend to considerable depth, below 10 km on the South Timmins seismic line, and the Dome mine is interpreted to lie above a north-dipping limb of these antiforms.

Finally, exposed granitoid plutons that core anticlines generally appear in both Abitibi and Yilgarn seismic profiles as bysmaliths or "surfboard" plutons, cylindrical shapes with steep sides and flat floors, about 3 km thick. The Yilgarn plutons are mapped (Swager et al., 1997) at depth by termination of reflections at their flanks, relatively isotropic and homogenous cores, and in the case of the Dunnsville pluton, by reflectors in the floor below the pluton that follow trends of the anticline. In the Timmins-Porcupine area, the syn-$D_1$ Adams pluton is relatively isotropic in terms of reflectors but is not flat floored. Reflectors beneath the pluton are concordant with the larger scale structures. Granite is not exposed at surface within the Shaw dome, but a thin, lenticular pluton is inferred at depth within the anticline core using the same criteria of truncated reflectors and isotropic, and thus nonreflective core. This may also represent a pre-$D_1$, synvolcanic pluton that channelled or concentrated deformation around its lenticular shape.

## Conclusions

Complementing previous seismic survey results in the Yilgarn, the new result of our seismic survey is that the Timmins region of the Abitibi subprovince is characterized by pervasive three-dimensional folds or thrust stacks throughout its upper crust and that regionally intact stratigraphy is not observed. This conclusion is consistent with earlier seismic profiling results farther east in the Abitibi subprovince, in the Wabigoon terrane of the western Superior craton, and in the northern Yilgarn craton of Australia. The current data on the full crust near Timmins is insufficient to allow interpretations or comparisons with these other areas, but a multilayered crust with dominantly northward dipping reflectors in the lower crust is indicated. Significantly for mineralization prospectivity studies, little direct evidence exists for individual fault or shear structures that penetrate the entire crust. This may indicate that faults are confined to the upper crust and truncated by detachments but most are probably obscured by pervasive alteration. Near Timmins the impedance structure of the entire crust appears to have been homogenized by locally pervasive mineralizing events so as to greatly subdue its overall reflectivity.

This survey used both a regional acquisition mode based on the latest LITHOPROBE surveys and a high-resolution mode to target specific mineralized structures in the uppermost few kilometers. Both modes are not possible simultaneously, yet each mode separately produced key results sought in designing this survey. Regional-scale broad folds and thrust stacks, imaged for the first time in this area, indicate that anticlines in the greenstone stratigraphy focussed syntectonic mineralizing fluids at many mine locations. If heterogeneous permeability occurs between different lithologic units, antiformal structures or domed roofs of intrusions will tend to focus fluids, whereas synforms will do the opposite, a simple consequence of geometry and upward fluid flow. High-resolution sections show aligned truncations of reflectors that indicate steeply dipping fault arrays, often coincident with the axial planes of the anticlines, which also channelled these fluids. This local superposition of folds and faults also suggested that major regional structures such as the Porcupine-Destor zone contain both of these structural elements, with isoclinal, detachment folding preceding transtensional faulting.

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## REFERENCES

Ayer, J., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K., and Trowell, N., 2002, Evolution of the southern Abitibi greenstone belt based on U-Pb geochronology: Authochthonous volcanic construction followed by plutonism, regional deformation and sedimentation: Precambrian Research, v. 115, p. 63–95.

Ayer, J.A., Berger, B.R., Hall, L.A.F., Houle, M.G., Johns, G.W., Josey, S., Madon, Z., Rainsford, D., Trowell, N.F., and Vaillancourt, C., 2005a, Geological compilation of the central Abitibi greenstone belt: Kapuskasing structural zone to the Quebec border: Ontario Geological Survey Preliminary Map P3565.

Ayer, J.A., Thurston P.C., Bateman R., Dubé B., Gibson H.L., Hamilton M.A., Hathaway B., Hocker S., Houlé M., Hudak G., Lafrance B., Lesher C.M., Ispolatov, V., MacDonald, P.J., Péloquin, A.S., Piercey S.J., Reed, L.E., and Thompson. P.H., 2005b, Overview of results from the Greenstone architecture project: Discover Abitibi Initiative Open File Report 6154, 146 p.

Barrie, C.T. and Davis, D.W., 1990, Timing of magmatism and deformation in the Kamiskotia-Kidd Creek area, western Abitibi subprovince, Canada: Precambrian Research, v. 46, p. 217–240.

Bateman, R., Ayer, J.A., Dubé, B., and Hamilton, M.A., 2005, The Timmins-Porcupine gold camp, northern Ontario—The anatomy of an Archean greenstone and its gold mineralization: Discover Abitibi initiative: Ontario Geological Survey Open File Report 6158, 90 p.

Bateman, R., Ayer, J.A., and Dubé, B., 2008, The Timmins-Porcupine gold camp, Ontario: Anatomy of an Archean greenstone belt and ontogeny of gold mineralization: ECONOMIC GEOLOGY, v. 103, p. 1285–1308.

Benn, K., 2006, Tectonic delamination of the lower crust during Late Archean collision of the Abitibi-Opatica and Pontiac terranes, Superior province, Canada: American Geophysical Union Geophysical Monograph Series 164, p. 267–282.

Benn, K., and Peschler, A.P., 2005, A detachment fold model for fault zones in the Late Archean Abitibi greenstone belt: Tectonophysics, v. 400, p. 85–104.

Berger, B.R., 2002, Geological synthesis of the Highway 101 area, east of Matheson, Ontario: Ontario Geological Survey Open File Report 6091, 124 p.

Bergman, B., Juhlin, C. and Palm, H., 2002, High-resolution reflection seismic imaging of the upper crust at Laxemar, southeastern Sweden: Tectonophysics, v. 355, p. 201–213.

Bleeker, W., 1995, Surface geology of the Porcupine camp: Geological Survey of Canada Open File 3141, p. 13–37.

Boyer, S.E. and Elliot, D., 1982, Thrust systems: American Association of Petroleum Geology Bulletin, v. 66, p. 1196–1230.

Calvert, A.J. and Ludden, J.N., 1999, Archean continental assembly in the southeastern Superior province of Canada: Tectonics, v. 18, p. 412–429.

Card, K.D., 1990, A review of the Superior province of the Canadian Shield, a product of Archean accretion: Precambrian Research, v. 48, p. 99–156.

Corfu, F., 1993, The evolution of the southern Abitibi greenstone belt in light of precise U-Pb geochronology: ECONOMIC GEOLOGY, v. 88, p. 1323–1341.

Corfu, F., and Noble, S.R., 1992, Genesis of the southern Abitibi greenstone belt, Superior province, Canada: Evidence from zircon Hf isotopic analyses using a single filament technique: Geochimica et Cosmochimica Acta, v. 56, p. 2081–2097.

Davis, W.J., Machado, N., Gariepy, C., Sawyer, E.W., and Benn, K., 1995, U-Pb geochronology of the Opatica tonalite-gneiss belt and its relationship to the Abitibi greenstone belt, Superior province, Quebec: Canadian Journal of Earth Sciences, v. 32, p. 113–127.

Drummond, B.J., Goleby, B.R., Goncharov, A.G., Wyborn, L.A.I., Collins, C.D.N., and MacCready, T., 1998, Crustal-scale structures in the Proterozoic Mount Isa inlier of north Australia: Their seismic response and influence on mineralization: Tectonophysics, v. 288, p. 43–56.

Goldfarb, R.J., Groves, D.I., and Gardoll, S.J., 2001, Orogenic gold and geologic time: A global synthesis: Ore Geology Reviews, v. 18, p. 1–75.

Goleby, B.R., Drummond, B.J., Swager, C.P., Williams, P.R., and Rattenbury, M.S., 1993, Constraints from seismic data on the regional and district scale structure of the Eastern Goldfields Province: AGSO Record, v. 1993/54, p. 85–90.

Goleby, B.R., Korsch, R.J., Sorjonen-Ward, P., Groenewald, P.B., Bell, B., Wyche, S., Bateman, R.J., Fomin, T., Drummond, B.J., and Owen, A.J., 2000, Crustal structure and fluid flow in the Eastern Goldfields, Western Australia: AGSO Record, v., 2000/34.

Goleby, B.R., Korsch, R.J., Fomin, T., Bell, B., Nicoll, M.G., Drummond, B.J., and Owen, A.J., 2002, Preliminary 3–D geological model of the Kalgoorlie region, Yilgarn craton, Western Australia, based on deep seismic-reflection and potential-field data: Australian Journal of Earth Sciences, v. 49, p. 917–935.

Goleby, B.R., Blewett, R.S., Korsch, R.J., Champion, D.C., Cassidy, K.F., Jones, L., Groenewald, P.B., and Henson, P.A., 2004, Deep seismic reflection profiling in the Archaean northeastern Yilgarn craton, Western Australia: Implications for crustal architecture and mineral potential: Tectonophysics, v. 388, p. 119–133.

Green, A.G., Milkereit, B., Mayrand, L., Ludden, J.N., Hubert, C., Jackson, S.L., Sutcliffe, R.H., West, G.F., Verpaelst, P., and Simard, A., 1990, Deep structure of an Archean greenstone terrane: Nature, v. 344, p. 327–330.

Hajnal, Z., Reed L.E., and Pandit B., 2006, Reprocessing and interpretation of Abitibi-Grenville line 12 for the Discover Abitibi seismic program: Discover Abitibi Initiative: Ontario Geological Survey Miscellaneous Release Data 196.

Jackson, S.L., and Fyon, J.A., 1991, The western Abitibi subprovince in Ontario:: Ontario Geological Survey Special Volume 4, Part 1, p. 405–482.

Jackson, S.L., Cruden, A.R., White, D. and Milkereit, B., 1995, A seismic-reflection-based regional cross section of the southern Abitibi greenstone belt: Canadian Journal of Earth Sciences, v. 32, p. 135–148.

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

MERQ-OGS, 1983, Lithostratigraphic map of the Abitibi subprovince: Ontario Geological Survey/Ministere de l'Energie et des Ressources, Quebec, cataloged as Map 2484 in Ontario and DV 83–16 in Quebec.

Moser, D.E., Heaman, L.M., Krogh, T.E., and Hanes, J.A., 1996, Intracrustal extension of an Archean orogen revealed using single-grain U-Pb zircon geochronology: Tectonics, v. 15, p. 1093–1109.

Owen, A.J., Bateman, R.J., Barton, T.J., Drummond, B.J., Goleby, B.R., and Sauter, P.C.C., 2001, Kalgoorlie seismic profiling 1997: Operations, processing, and interpretation report: AGSO Record, v. 2001/16.

Percival, J.A., and West, G.F., 1994, The Kapuskasing uplift: A geological and geophysical synthesis: Canadian Journal of Earth Sciences, v. 31, p. 1256–1286.

Percival, J.A., Bleeker, W., Cook, F.A., Rivers, T., Ross, G., and van Staal, C., 2004, PanLITHOPROBE Workshop IV: Intra-orogen correlations and comparative orogenic anatomy: Geoscience Canada, v. 31, p. 23–39.

Perron, G., Milkereit, B., Reed, L.E., Salisbury, M., Adam, E. and Wu, J., 1997, Integrated seismic reflection and borehole geophysical studies at Les Mines Selbaie, Quebec: Canadian Institute of Mining and Metallurgy Bulletin, v. 90, p. 75–82.

Peschler, A.P., Benn, K., and Roest, W.R., 2004, Insights on Archean continental geodynamics from gravity modelling of granite-greenstone terranes: Journal of Geodynamics, v. 38, p. 185–207.

Reed, L.E., 2005a, Magnetic and gravity three dimensional (3D) modeling: Discover Abitibi Initiative: Ontario Geological Survey Open File Report 6163, 40 p.

——2005b, Magnetic and gravity three dimensional (3D) modeling: Discover Abitibi Initiative: Ontario Geological Survey Miscellaneous Release, Data 162.

Reed, L.E., Snyder, D.B., and Salisbury, M., 2005, 2D reflection seismic surveying in the Timmins /Kirkland Lake area, northern Ontario, Canada: Acquisition, processing, interpretation: Discover Abitibi Initiative: Ontario Geological Survey Open File Report 6169, 68 p.

Robert, F., and Poulsen, K.H., 2001, Vein formation and deformation in greenstone gold deposits: Reviews in Economic Geology, v. 14, p. 111–155.

Ropchan, J.R., Luinstra, B., Fowler, A.D., Benn, K., Berger, B.R., Dahn, R., Labine, R. and Amelin, Y., 2002, Host-rock and structural controls on the nature and timing of gold mineralization at the Holloway mine, Abitibi subprovince, Ontario: ECONOMIC GEOLOGY, v. 97, p. 291–309.

Salisbury, M. H., Milkereit, B., Ascough, G., Adair, R., Matthews, L., Schmitt, D.R., Mwenifumbo, J., Eaton, D.W., and Wu, J., 2000, Physical properties and seismic imaging of massive sulfides: Geophysics, v. 65, p. 1882–1889.

Salisbury, M.H., Harvey, C.W., and Matthews, L., 2003, The acoustic properties of ores and host rocks in hardrock terranes: Society of Exploration Geophysicists, Geophysical Developments Series 10, p. 9–19.

Swager, C.P., Goleby, B.R., Drummond, B.J., Rattenbury, M.S., and Williams, P.R., 1997, Crustal structure of granite-greenstone terranes in the Eastern Goldfields, Yilgarn craton, as revealed by seismic reflection profiling: Precambrian Research, v. 83, p. 43–56.

Verpaelst, P., Peloquin, A.S., Adam, E., Barenes, A.E., Ludden, J.N., Dion, D.J., Hubert, C., Milkereit, B., and Labrie, M., 1995, Seismic reflection profiles across the Mine Series in the Noranda camp of the Abitibi belt, eastern Canada: Canadian Journal of Earth Sciences, v. 32, p. 167–176.

White, D.J., Musacchio, G., Helmstaedt, H.H., Harrap, R.M., Thurston, P.C., vander Velden, A., and Hall, K., 2003, Images of a lower-crustal oceanic slab: Direct evidence for tectonic accretion in the Archean western Superior province: Geology, v. 31, p. 997–1000.

# APPENDIX

## Deep Seismic Reflection Profiles

*Parameters used for seismic reflection data acquisition*

| Parameter | Regional mode | High-resolution mode |
|---|---|---|
| Record length | 12 s | 6 s |
| Sample interval | 2 ms | 2 ms |
| Channels | 961 max | 795 max |
| Geophones | Single three-component phone (I/O VectorSeis SVSM) | |
| Group interval | 25 m | 12.5 m |
| Source | 3 to 4 vibrators | 2 vibrators |
| | Inline over 27 m | Inline over 18 m |
| | 6 sweeps of 28 s | 3 sweeps of 28 s |
| | 10 to 96 Hz linear sweep | 10 to 160 Hz |
| | | Nonlinear: +3 dB/octave |
| Source interval | 50 m | 25 m |
| Nominal spread | 12000-0-12000 m | 6000-0-6000 m |
| Nominal fold | 240,000 percent | 24,000 percent |
| Filters | ? Nyquist, | Minimum phase with notch out |

*Processing stream for regional lines*

SEG-Y reformat
Geometry and crooked line (CDP) binning
Trace edits and/or kills
Spherical divergence amplitude correction
Spiking deconvolution: 100 ms operator, design window offset dependent
Refraction statics correction: 300 m datum elevation, 6,000 m/s velocity
Velocity analysis
Surface-consistent statics
Shot-domain f-k polygon filter after temporary NMO and AGC
Receiver-domain f-k polygon filter after temporary NMO and AGC
Spiking deconvolution: 100 ms operator, design window offset dependent
Time-variant spectral whitening with bandwidth 4/10 to 96/120 Hz
Velocity analysis
Surface-consistent statics
Normal move out correction
Automatic gain control with 1,000 ms window
CDP stack within common offset bins: 12.5-m spacing
F-X predictive filter
Automatic gain control with 1,000 ms window
Dip moveout correction
Front mutes
Automatic gain control with 1,000 ms window
CDP stack
Anisotropic diffusion filter
Time-variant Bandpass filter: 5/10 to 100/120 Hz @ 0 to 2 s
5/10 to 40/60 Hz @ 3.5 to 12 s
Trace equalization
Implicit finite-difference time migration: 0° to 65°
Bandpass filter: 10/20 to 120/140 Hz