GAC MEDALLIST SERIES

Logan Medallist 2. Geophysics and Geology: An Essential Combination Illustrated by *LITHOPROBE* Interpretations–Part 1, Lithospheric Examples

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SUMMARY
Lithoprobe (1984–2005), Canada's national, collaborative, multidisciplinary, Earth science research project, investigated the structure and evolution of the Canadian landmass and its margins. It was a highly successful project that redefined the nature of Earth science research in Canada. One of many contributions deriving from the project was the demonstration by example that Earth scientists from geophysics and geology, including all applicable sub-disciplines within these general study areas, must work together to achieve thorough and comprehensive interpretations of all available data sets. In this article, I exemplify such contributions by summarizing interpretations of lithospheric structure and development from Lithoprobe journal publications relating to eleven specific regions in Canada. Four of the examples derive from studies in the Mesozoic–Cenozoic Canadian Cordillera: the original Lithoprobe program on Vancouver Island, the region of the Monashee Mountains in the southeastern Cordillera, allochthonous and autochthonous terranes in the northwestern Cordillera, and the craton-Cordillera transition in northeastern British Columbia. Two examples represent the Paleozoic Appalachians in Newfoundland. One of these shows crustal structure across the southwestern part of the island; the other shows a more detailed study on the southwestern coast. The Mesoproterozoic Grenville Province is the focus of two examples. One shows crustal structure from the Archean Pontiac metasedimentary sub-province across the Grenville Front and the exposed southeastern part of the province; the other illustrates two- and three-dimensional interpretation in the central Grenville Province. Lithoprobe supported research in the development of geodynamical modelling techniques and the application of these to tectonic processes inferred within transect study areas. Such work is exemplified through a comparison of a numerical model developed for the southwestern Grenville orogen and comparison of model results with those from geophysical and geological studies. Lithoprobe carried out extensive research in the Paleoproterozoic Trans-Hudson Orogen in Saskatchewan and Manitoba. Some early results from the interpreted seismic results completely revised previous results based on geology only and fostered additional geological studies. This is illustrated by studies over an Archean window in the middle of the orogen. The final example derives from studies in the westernmost part of the Archean Superior Province in western Ontario. It focuses on the derivation of near-surface velocity information from the seismic reflection data and the relationship of this information to the known geology.

SOMMAIRE
Lithoprobe (1984–2005) est ce projet de recherche national canadien, multidisciplinaire et coopératif en science de la Terre, qui a étudié la structure, l'évolution et les marges de la masse continentale du Canada. Ce fut un projet très réussi qui a redéfini la nature de la recherche en sciences de la Terre au Canada. L'une des nombreuses répercussions de ce projet a été la démonstration que les scientifiques de la Terre en géophysique et en géologie, y compris tous les sous-disciplines applicables de ces domaines d'études générales, doivent collaborer pour espérer obtenir des interprétations rigoureuses et exhaustives de tous les ensembles de données disponibles. Dans cet article, j'illustre des contributions de ce genre en résumant les interprétations structurales et l'évolution de la lithosphère à partir des publications de Lithoprobe dans des revues portant sur onze régions définies du Canada.

Geoscience Canada, v. 42, http://dx.doi.org/10.12789/geocanj.2014.41.064

Quatre des exemples proviennent d'études du Mésozoïque-Cénozoïque dans la Cordillère canadienne : le programme Lithoprobe d'origine sur l'île de Vancouver, la région des montagnes Monashee dans le sud-est de la Cordillère, les terranes allochtones et autochtones dans le nord-ouest de la Cordillère, et la transition du craton à la Cordillère nord-est de la Colombie-Britannique. Deux exemples représentent le Paléozoïque des Appalaches à Terre-Neuve. L'un de ces exemples révèle l'existence d'une structure crustale dans la partie sud-ouest de l'île; l'autre est une étude plus détaillée de la portion sud-ouest de la côte. Le Mésoprotérozoïque de la Province de Grenville est l'objet de deux exemples. Un exemple révèle la structure de la croûte de la sous-province archéenne de roches métasédimentaires Pontiac à travers le front de Grenville et la partie sud-est de la Province qui affleure; l'autre est une interprétation en deux et trois dimensions de la portion centrale de la Province de Grenville. Lithoprobe a favorisé la recherche de mise au point de techniques de modélisation géodynamique et l'application de celles-ci à des processus tectoniques présumés dans les zones d'étude de transects. Ce travail est illustré par une comparaison d'un modèle numérique développé pour la portion sud-ouest de l'orogène de Grenville et la comparaison des résultats du modèle avec ceux des études géophysiques et géologiques. Lithoprobe a réalisé des recherches approfondies de l'orogène trans-hudsonien en Saskatchewan et au Manitoba. Certains des premiers résultats basés sur l'interprétation des données sismiques ont complètement remis en question les résultats précédents basés sur la géologie seulement, et justifié des études géologiques supplémentaires. Ceci est illustré par des études sur une fenêtre archéenne au milieu de l'orogène. Le dernier exemple provient d'études réalisées dans la partie la plus à l'ouest de la Province du Supérieur archéenne de l'ouest de l'Ontario. Il porte sur des informations déduites des vitesses sismiques de faibles profondeurs sur des données de sismique réflexion et de la relation de ces informations avec la géologie connue.

INTRODUCTION

Lithoprobe was Canada's national, collaborative, multidisciplinary, Earth science research project that was active from 1984 to 2005 (Clowes 2010a). The project was established to develop a comprehensive understanding of the structure and evolution of Canada's present landmass and continental margins, which are a complex geological mosaic representing more than four billion years of development. Its principal scientific and operational components were built around a series of ten transects or study areas (Fig. 1), each of which was focused on carefully selected geological features that represent globally significant geotectonic processes. For each transect, an integrated scientific program addressed fundamental problems of the structure and evolution of the lithosphere and was carried out by a multidisciplinary transect team. This program was spearheaded by seismic reflection investigations but necessarily all other applicable geological, geochemical and geophysical subdisciplines within the solid Earth sciences provided the scientific context that bound the program into a cohesive, comprehensive investigation.

Lithoprobe was highly successful and is regarded nationally and internationally as an outstanding example of collaborative and multidisciplinary Earth science research. On a scientific basis, more than 1500 publications were generated and are available on a searchable data base at the Lithoprobe web site, www.Lithoprobe.ca . Syntheses of individual study areas are published in special issues of *Canadian Journal of Earth Sciences* (*CJES*); references are included in the data base. More recently, two pan-Lithoprobe syntheses (Clowes 2010b; Percival et al. 2012) tie the various elements of the project together and highlight many important aspects of the scientific accomplishments.

The Lithoprobe research network redefined the nature of much Earth science research in Canada. It successfully fostered an unprecedented degree of cooperation among Earth scientists in universities, federal and provincial/territorial geological surveys, and the mining and petroleum industries. It spawned a new and healthy atmosphere of scientific cooperation among geologists, geophysicists, and geochemists, all of whom worked and learned together, thereby enhancing results beyond those that could be achieved through any one subdiscipline. Lithoprobe literally changed the face of Earth science research in Canada.

In this article, I emphasize the latter point: geophysicists and geologists (in the broadest sense of the terms) must work together, and geophysical and geological data must be combined, to achieve the most thorough and comprehensive interpretation of those data, including extension of the interpretation into the third dimension, depth. To exemplify this important statement, I have selected a series of examples from the many Lithoprobe publications in which a combination of geophysics and geology led to high quality interpretations. The geophysical data are primarily seismic reflection because such data provide the highest resolution for tying with geology, but other geophysical data also are exemplified. The geological data are primarily maps because they tie best with the geophysical data for subsurface interpretations, but other geological data also are included. However, maps usually derive from a range of geological information, such as field, structural, metamorphic, geochemical and dating studies, and thus represent a more comprehensive analysis of a region than the typical 2-D display might indicate.

Because Lithoprobe's primary objective was lithospheric structure, this aspect of the project forms Part 1 of the set of examples and represents the current contribution. However, Lithoprobe also generated economic benefits for Canada, particularly those related to exploration for base metals, uranium, diamonds and petroleum, and better understanding of the environments in which such exploration takes place. Accordingly, the set of examples in Part 2 (to be published separately) focuses on combined interpretations in the exploration environment. In effect, the sets of examples in parts 1 and 2 constitute a review of some of the important Lithoprobe results derived from a combination of geophysical and geological data. In some cases, subsequent research within and outside

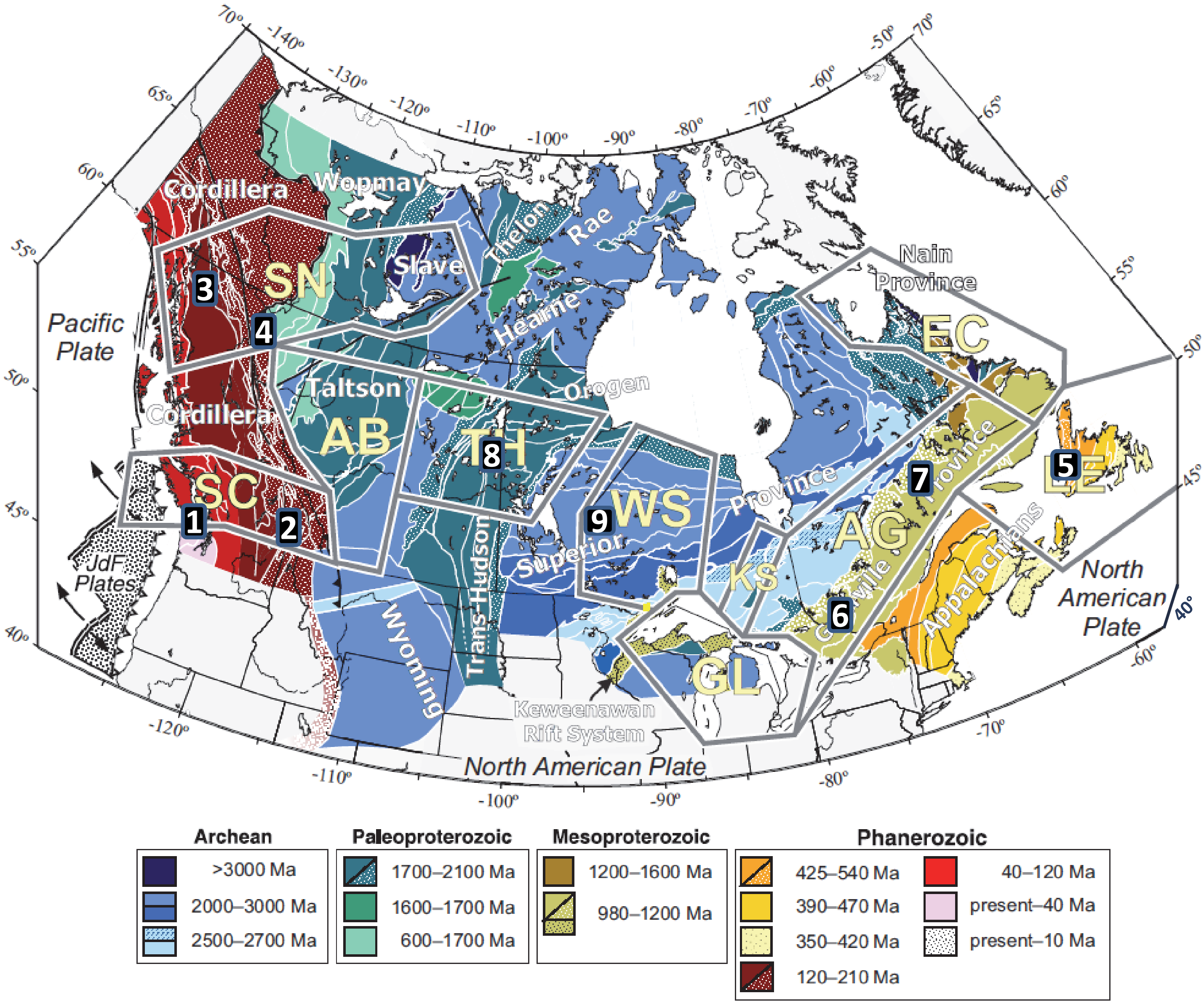

Figure 1. Simplified tectonic age map of Canada with outlines of Lithoprobe transects. White lines indicate domain divisions within the major tectonic elements. Stippling of some coloured areas indicates that the rocks may be older but they have experienced tectonic reworking during the time periods indicated by the colour. Numbers identify the general locations of subsequent map figures referenced in the text and other captions. Transect abbreviations: AB, Alberta Basement; AG, Abitibi-Grenville; EC, Eastern Canadian Shield Onshore-Offshore Transect (ECSOOT); GL, Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE); KS, Kapuskasing Structural Zone; LE, Lithoprobe East; SC, Southern Cordillera; SN, Slave-Northern Cordillera Lithospheric Evolution (SNORCLE); TH, Trans-Hudson Orogen (THOT); and WS, Western Superior.

of Lithoprobe has revised interpretations relative to the original ones but the examples in this paper focus on the original publications.

VANCOUVER ISLAND AND THE INITIATION OF LITHOPROBE

Lithoprobe received funding in 1984 for a 1-year initial, or test, phase of its multidisciplinary research plans. It had to be successful and it was. Southern Vancouver Island was selected as the primary focus of study. With the available funds, 206 km of multichannel seismic reflection data were recorded along four lines, two of which are located in Figure 2a. The objective of the survey was to demonstrate the applicability of the reflection method to provide the third dimension of geology to depths as great as the base of the crust and to image the Juan de Fuca plate below Vancouver Island, if possible. Data were acquired and processed by industry contractors.

In October 1984, four geophysicists and three geologists gathered at the Pacific Geoscience Centre on Vancouver Island to study the seismic images provided by the contractors. Much discussion occurred but finally a consensus on interpretation was reached. Subsequently, a series of papers were published (Yorath et al. 1985; Green et al. 1986; Clowes et al. 1987). Figure 2b and 2c, extracted

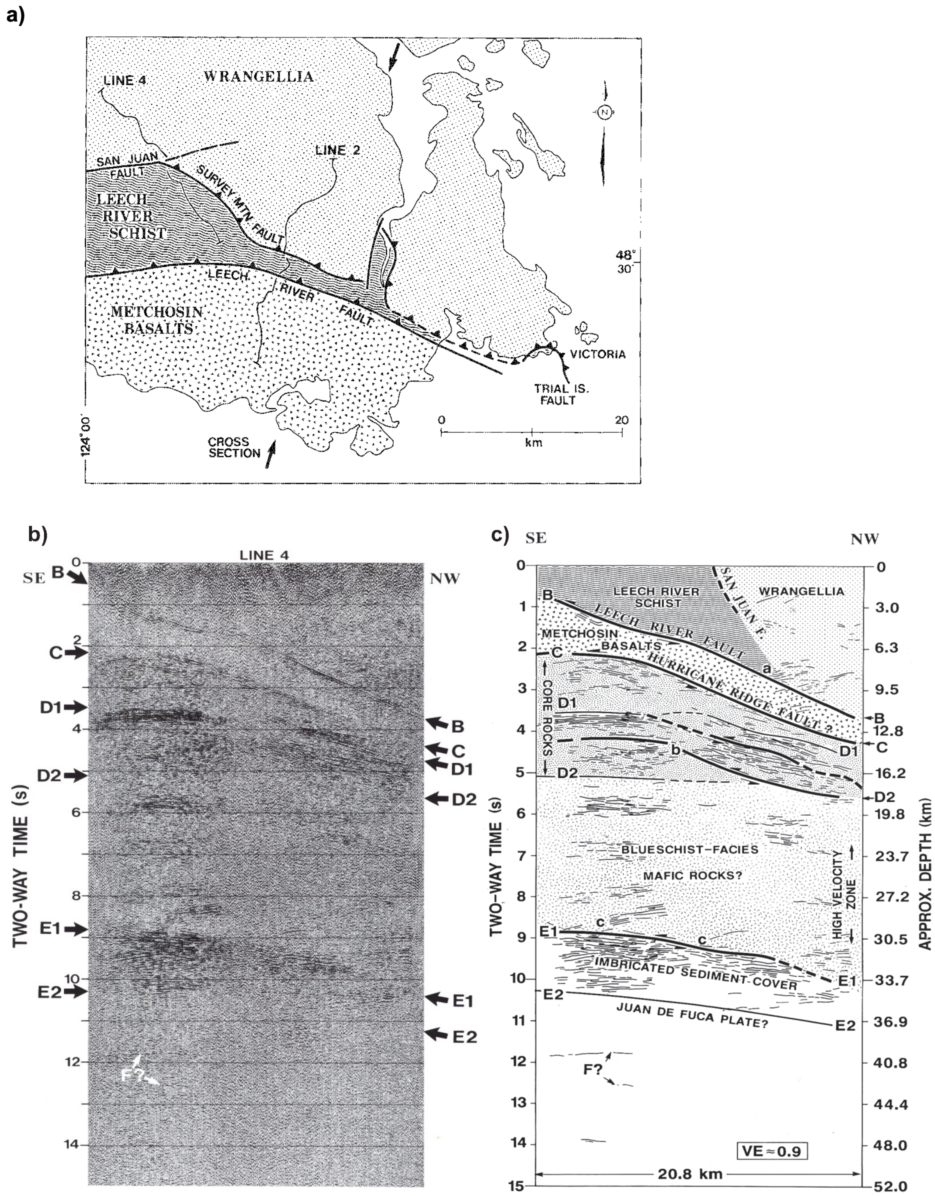

Figure 2. *(a)* Simplified geological map of southern Vancouver Island (location 1 in Fig. 1) showing locations of Lithoprobe lines 2 and 4. *(b)* Seismic reflection results for Vancouver Island Line 4; no migration. Letters identify reflection features, the important ones of which are identified in (c). Vertical exaggeration is ~ x 0.9, based on an average velocity of 6.6 km/s. *(c)* Geologic interpretation superimposed on a line drawing of the record section. The approximate depth scale is based on the refraction results of Spence et al. (1985). From Clowes et al. (1987).

from Clowes et al. (1987), show the data and interpretation for Line 4. Data quality is excellent with coherent reflections recorded between 0.5 and 14.0 s (two-way travel time on the seismic record). Although limited outcrops occur in the region, the principal geological units and faults were well identified on geological maps (Fig. 2a). The Leech River fault, the boundary between the Leech River schist and the Metchosin basalt, is clearly imaged (Fig. 2c). Another fault, Hurricane Ridge, known to exist to the south on the Olympic Peninsula of Washington State and separating the basalt unit from core rocks of the peninsula, is interpreted as event C on the data section. Although Line 4 crossed the San Juan Fault, it was not imaged on the seismic section. However, subsequent specialized processing of data along the line indicated that a steeply dipping (60° to 80°) reflector was recorded and probably represents reflections from the San Juan Fault (Mayrand et al. 1987). The primary and most significant interpreted result from Line 4 and the other lines was the imaging of the top of the Juan de Fuca plate beneath Vancouver Island (event E2) and probably the top of the imbricated sedimentary rocks that were subducted with the plate (event E1). In this interpretation, event F, imaged much more clearly on Line 2 (Clowes et al. 1987), is tentatively associated with the oceanic Moho of the subducting plate. Unfortunately, these deep reflections could not be tied directly with any geological feature.

Research on the Cascadia subduction zone has continued to the present day due to interest in such structures and the possibility of a future megathrust earthquake in the region (e.g. Hyndman 1995). However, controversy regarding the positions of the subducting Juan de Fuca plate and the continental Moho beneath Vancouver Island also remains, as interpretations of active source seismic data (e.g. Calvert et al. 2011) differ considerably from those based on teleseismic data (e.g. Nicholson et al. 2005). In a recent paper, Bostock (2013) attempted to reconcile the differences.

MONASHEE MOUNTAINS OF THE SOUTHERN CORDILLERA

Carrying on from the Vancouver Island survey and work in the southeastern Cordillera (Cook et al. 1988), Lithoprobe acquired reflection data along a series of profiles across the southern Cordillera of British Columbia in 1988 (Cook et al. 1992; Varsek et al. 1993). Good geological information was available (e.g. Monger 1989; Wheeler and McFeeley 1991; Gabrielse et al. 1992). Surface structures provided evidence of 25 km or more of structural relief. Some of these could be readily correlated with structures that were outlined by the reflection images and could be followed into the middle and lower crust. This enabled clear distinction between structures caused by compressional deformation, resulting from Jurassic to Eocene convergence between accreted terranes and North America, and those caused by later Eocene extension.

Figure 3 shows one example,

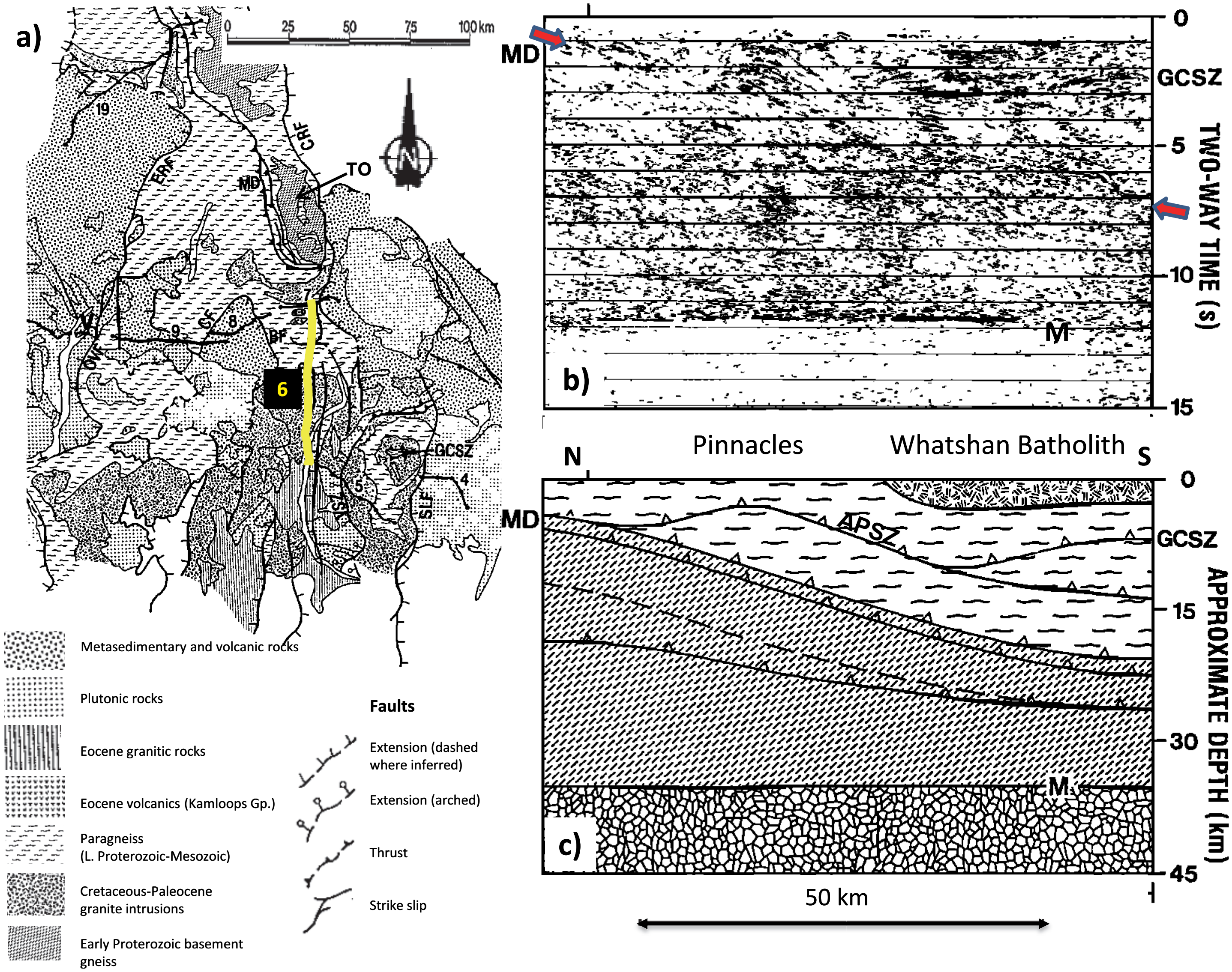

Figure 3. *(a)* Geological map and legend for the region of the Monashee Mountains in the southeastern Canadian Cordillera (location 2 in Fig. 1). The location of Line 6 is highlighted. Modified from figure 2 in Cook et al. (1992). TO is Thor-Odin culmination; V is Vernon antiform. Fault abbreviations: BF, Beavan; CF, Cherryville; CRF, Columbia River; ERF, Eagle River; GCSZ, Gwillim Creek shear zone (see Fig. 4); OVF, Okanagan Valley; SLF, Slocan Lake; VSZ, Valkyr shear zone. *(b)* Migrated and coherency filtered reflection data from Line 6. Note the south-dipping layers that flatten above 7.0 s and the prominent Moho (M, base of the crust) at ~11.8 s. Arrows show reflections identified as the Monashee decollement (MD); GCSZ is the Gwillim Creek shear zone (Fig. 4). *(c)* Interpretation of Figure 3b that incorporates the surface geology. APSZ is the Arrow Park shear zone, an inferred thrust fault. Lines below MD, such as the thrust fault, are drawn to be consistent with boundaries on lines 5 and 7 (locations in (a)) and illustrate the general trend of reflectivity in this part of the line. Parts (b) and (c) from figure 3 in Cook et al. (1992).

north-south Line 6, which joins east-west lines 4/5 with east-west lines 7/8/9. From north to south, the line crosses the southern flank of the Thor-Odin culmination (part of the high-grade Monashee complex; Reesor and Moore 1971), the Pinnacles culmination and the Whatshan batholith (Read 1979). One of the most prominent features on the interpretation (Fig. 3c) is the Monashee decollement (MD; e.g. Brown et al. 1992), a southwest-dipping shear zone with late Proterozoic to Mesozoic paragneiss in its hanging wall and early Proterozoic basement gneiss units of North America in its footwall. It is interpreted on the basis of a south-dipping band of reflections that extends from about 1.5 s in the north to 7.0 s at the south end, these reflections forming a boundary against which adjacent reflections are truncated. Above MD and just north of the middle of the profile, the data section (Fig. 3b), shows arcuate structures between 0 and 3.5 s; these structures match the position of the Pinnacles culmination. The latter and the corresponding synform to its north are cut off at the Monashee decollement, thereby forming a hanging wall antiform/synform pair. Extending south from the Pinnacles structure is another south-dipping structure that tends to truncate sub-horizontal reflections above it, suggesting another, structurally higher and quasi-parallel fault above the MD, subsequently referred to as the (inferred) Arrow Park shear zone (Carr 1995).

On the southern end of the profile, a strong reflection dipping north from about 2 to 3 s is interpreted as the Gwillim Creek shear zone (GCSZ) based on its likely tie with a strong reflection on Line 5 (Fig. 3a) that is associated with the shear zone, which has a surface exposure about 30 km east of the south end of Line 6 (Fig. 3a; Cook et al. 1988). The GCSZ is interpreted as a deep-seated thrust, part of the thrust system that accommodated eastward shortening of the Foreland belt in the late Cretaceous and Paleocene (Brown et al. 1992). A field view of the GCSZ (Fig. 4) shows it as a large structure with subhorizontal sheets of paragneiss, orthogneiss and granite, which probably account for its strong image on the reflection section (Fig. 3b). It is structurally higher than the Arrow Park thrust beneath Pinnacles, but both were carried in the hanging wall of the Monashee decollement as deformation progressed eastward and to deeper structural levels. Age constraints indicate that the Gwillim Creek shear zone is older (Late Cretaceous) than the deeper Arrow Park thrust and Monashee decollement, which have ages of about 77 Ma and >58 Ma, respectively (Carr 1995), as might be expected in a propagating thrust system.

The Whatshan batholith is a Late Cretaceous feature that extends over an area in excess of 1000 km^2. Seismic reflection data on the south end of Line 6 (a strong reflector between 1.0 and 1.3 s) indicate that the batholith is sheet-like in nature and probably 2–3 km thick. The strong reflector is cut off at its northern end, consistent with the termination of the surface exposure of the batholith.

Figure 4. Photograph of the Gwillim Creek shear zone, which includes sheets of paragneiss, orthogneiss and granite. This package of rocks is interpreted to be the source of the strong reflections identified on Figure 3b. Total height of cliff face is about 100 m; note trees in the foreground. From Clowes et al. (1992); photograph courtesy of R. Parrish, then with the Geological Survey of Canada.

INTERMONTANE SUPERTERRANE, NORTHERN CORDILLERA

Like the southern Cordillera, the northern Canadian Cordillera developed on the western edge of North America, primarily from middle Paleozoic through to Paleogene times, but was not characterized by subduction from the latter time to the present as is the case in the south. This development generated well-studied surface rocks that consist of North American marginal strata ranging in age from Paleoproterozoic to Paleozoic, pericratonic and allochthonous terranes accreted during Mesozoic to Paleogene orogenesis, and synorogenic to post-orogenic igneous and sedimentary rocks (Fig. 5; Wheeler and McFeeley 1991; Gabrielse et al. 1992). Accretion resulted in east-northeast contraction followed by a series of northwest-striking dextral strike-slip faults, the most prominent of which is the Tintina Fault-Northern Rocky Mountain Trench (TF-NRMT) fault system. The extent and timing of displacement along the TF-NRMT system has been a subject of debate for many years; more recent geological evidence indicates about 420 km of displacement during the Early Paleogene (Jackson and Mortensen 2000).

During the fall/winter of 1999–2000, Lithoprobe acquired more than 1900 km of reflection data along three major profiles, two of which are located in Figure 5; Line 3 is further north in the Yukon. Cook et al. (2004) provided a comprehensive discussion of the complete data set. Figure 6 shows the data and interpretation for the northern half of Line 2a (location in Fig. 5) as generated by Evenchick et al. (2005) through a more detailed look at the specific geology in relation to the seismic data along the profile. Starting from the north, the most prominent feature is the Tintina Fault-Northern Rocky Mountain Trench (TF-NRMT), which is identified by a vertical zone with a lack of reflectivity to at least the base of the crust. This same characteristic is observed on the two other reflection profiles that cross the fault zone, providing strong indication that the TF-NRMT extends through the crust and probably into the upper mantle.

Lithoprobe magnetotelluric (MT) data, acquired on three profiles that cross the TF-NRMT, are consistent with this interpretation. Resistivity models derived from the data show a pronounced change in resistivity values below the fault zone relative to those on either side (Fig. 7; Ledo et al. 2002). Values in the middle and lower crust beneath the fault zone are highly resistive, which contrasts with some other large-scale strike-slip faults. Ledo et al. (2002) suggested that the latter point implies that fault zone processes that

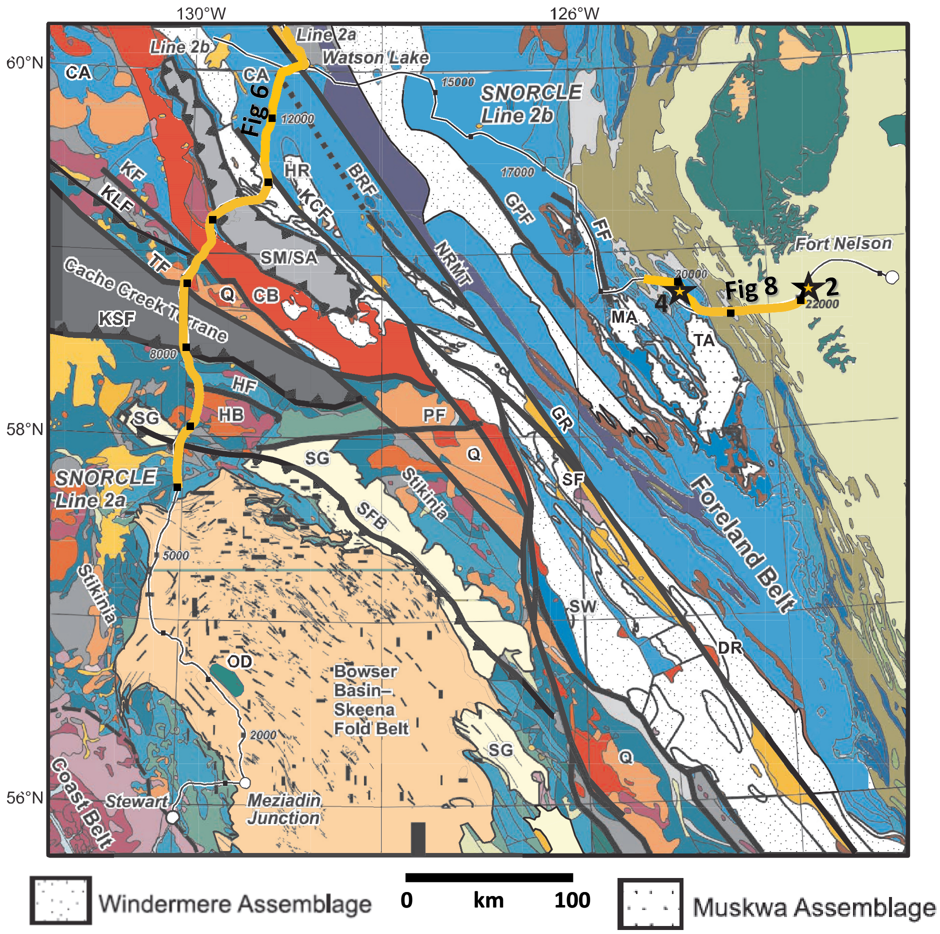

Figure 5. General geological map for northern British Columbia showing the locations of SNORCLE lines 2a and 2b (locations 3 and 4 in Fig. 1; from Evenchick et al. 2005, which was modified from Wheeler and McFeeley 1991). VP (station) locations are indicated by squares for every 1000 stations. Lines highlighted in gold colour show locations of data in Figures 6 and 8. Stars show locations of refraction shot points 2 and 4 (see Fig. 8). Heavy lines are major faults; dash-dot line in SW corner is the boundary between Coast and Intermontane belts. Abbreviations: BRF, Burnt Rose Fault; CA, Cassiar Terrane; CB, Cassiar Batholith; DR, Deserters Range; FF, Forcier Fault; GPF, Gundahoo Pass Fault; GR, Gataga Range; HB, Hotailuh batholith; HF, Hotailuh Fault; HR, Horseranch Range; KCF, Kechika Fault; KF, Kutcho Fault; KLF, Klinkit Fault; KSF, King Salmon Fault; MA, Muskwa Anticlinorium; OD, Oweegee Dome; PF, Pitman Fault; Q, Quesnellia; SFB, Front of Skeena Fold Belt; SF, Sifton Ranges; SG, Sustut Group; SM/SA, Slide Mountain Terrane – Sylvester Allochthon; SW, Swannell Range; TA, Tuchodi Anticline; TF, Thibert fault. Heavy lines in the Bowser Basin are average structural trends based on > 15,000 bedding measurements; light lines are axial surface traces of individual folds.

result in interconnecting conducting phases (and hence low resistivity) are not generic in nature but are controlled by local conditions.

Geochemical studies of Tertiary to Recent alkaline lavas across the northern Cordillera provide further evidence that the TF-NRMT extends into the sub-crustal lithosphere (Abraham et al. 2001). Chemical changes and discontinuities in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios in basalt from volcanic centres situated across the TF-NRMT indicate that it is a high-angle fault that penetrates the lithosphere and juxtaposes two distinct lithospheric mantles. However, the nature and origin of the lithospheric mantle are not well constrained (Abraham et al. 2001).

South of the TF-NRMT, the seismic data and geological information enable a detailed interpretation (Fig. 6). Evenchick et al. (2005) suggested a general division into three broad zones. The first zone is the upper crustal region with weak to moderate and discontinuous reflections from the TF-NRMT south to the Thibert fault. A somewhat stronger upper crustal reflectivity extends to the end of Figure 6 and further south to the end of the line (see Evenchick et al. 2005 for the complete section). Within this zone, the geology is well related to the seismic data. Most of the known faults (Fig. 5) are shown to sole listrically into the upper or middle crust; they do not penetrate through the crust. Only the Thibert fault is interpreted to extend into the lower crust. Most terranes identified on the surface (e.g. Cassiar, Slide Mountain, Quesnellia and Cache Creek) are shown to be relatively thin slices from about 3 to 6 km thick. The one exception is Stikinia which appears to have ramped up over older strata and south of station 7000 includes a full crustal section extending to the Moho.

The second zone inferred by Evenchick et al. (2005) is a mid and lower crustal wedge with numerous strong, dipping and continuous reflections. The wedge tapers southwest to end roughly below station 7000. It is interpreted to comprise pre-existing North American Paleoproterozoic basement rocks onto which accretion took place, as indicated by the 'tectonic accretion surface' (Fig. 6). Above this surface and below the upper crustal features, a region of tectonically interleaved rocks (including the Neoproterozoic Windermere assemblage, some Paleozoic strata, and the Quesnellia and Stikinia terranes, all of which outcrop at some point) is inferred. The third zone is the southwestern part that spans the crust and shows generally less reflectivity than within the wedge but considerably more continuous and numerous reflections than the upper crust northeast of the Thibert fault. Most of this zone is associated with the Stikinia terrane but individual reflections within the terrane are difficult to interpret.

MUSKWA UPLIFT AND THE CRATON-NORTHERN CORDILLERA TRANSITION

SNORCLE Line 2b, which runs along

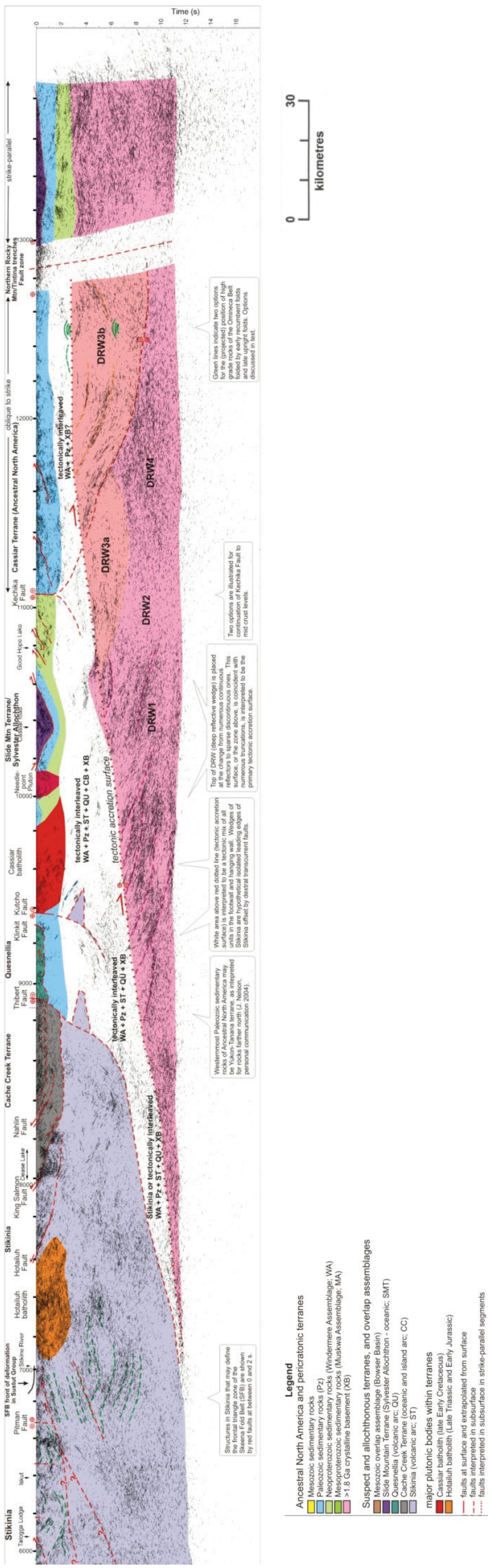

Figure 6. Interpreted seismic reflection section for Line 2a; from vibration point 6000 north to the end of the line (location in Fig. 5). Horizontal axis numbers are vibration points. Two-way travel time is given by vertical axis at right of section. Scale is ~ 1:1. Not all units shown in the legend are included in this segment of the interpretation. From Evenchick et al. (2005).

the Alaska Highway from west of Watson Lake, Yukon, eastward to Fort Nelson, B.C (Fig. 5), was planned to provide a westward-extending link with Line 1 in the Northwest Territories. Line 1 extends westward from the southwest Slave craton across the different components of the Paleoproterozoic Wopmay Orogen that lie below the Western Canada Sedimentary Basin (WCSB; Cook et al. 1999) to link with Line 2b, albeit with an along-strike southerly offset of about 250 km. Line 2b extends westward from the WCSB across the Cordilleran deformation front and the deformed North American rocks of the Foreland belt to just west of the Tintina fault (Fig. 5), with the scientific objective of examining the crustal structure of all of these elements.

Figure 8a shows reflection data for the section of the line that crosses the deformation front and lies just north of two inliers in which the Tuchodi and Muskwa anticlinoria are exposed (TA and MA, respectively, in Fig. 5), of the Proterozoic Muskwa assemblage (age 1.8 to 1.2 Ga), a metamorphosed sedimentary package. The Muskwa assemblage, comprising seven mapped formations, has a composite thickness of at least 5.4 km even though its base is not exposed (Aitken and McMechan 1991; Cook and Siegel 2006). Uplift of the Muskwa anticlinorium appears to have occurred through at least two orogenic episodes, the first sometime after the sediments were deposited but prior to the Cambrian, and the second during Mesozoic Cordilleran orogenesis (Ross et al. 2001; Cook and Siegel 2006). Interpretation of the seismic reflection image (Fig. 8a) illustrates some of this development. Based on ties with surface geology and the seismic section, Mesoproterozoic strata were deposited onto the Muskwa assemblage (upper left, Fig. 8a). The second orogenic episode is clearly reflected in the seismic image and its interpretation. The combined Proterozoic strata were thrust up and eastward over older or equivalent Paleoproterozoic strata and tectonically wedged into Paleozoic and Mesozoic strata of the Foreland belt. The lowermost part of the crust is inferred to be North American basement that is older than 1.8 Ga.

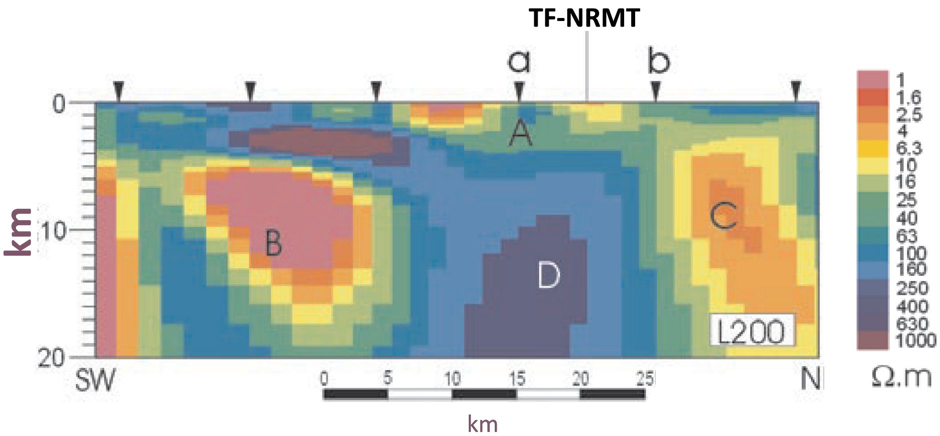

Figure 7. Two-dimensional resistivity model obtained by inversion of magnetotelluric data recorded across the Tintina Fault-Northern Rocky Mountain Trench (TF-NRMT) near Watson Lake (Fig. 5). Points 'a' and 'b' identify MT station sites on either side of the locus of the TF-NRMT. Note the lateral contrast in resistivity between the region below the fault (A, D) and regions to either side (B, C). From figure 4 of Ledo et al. (2002).

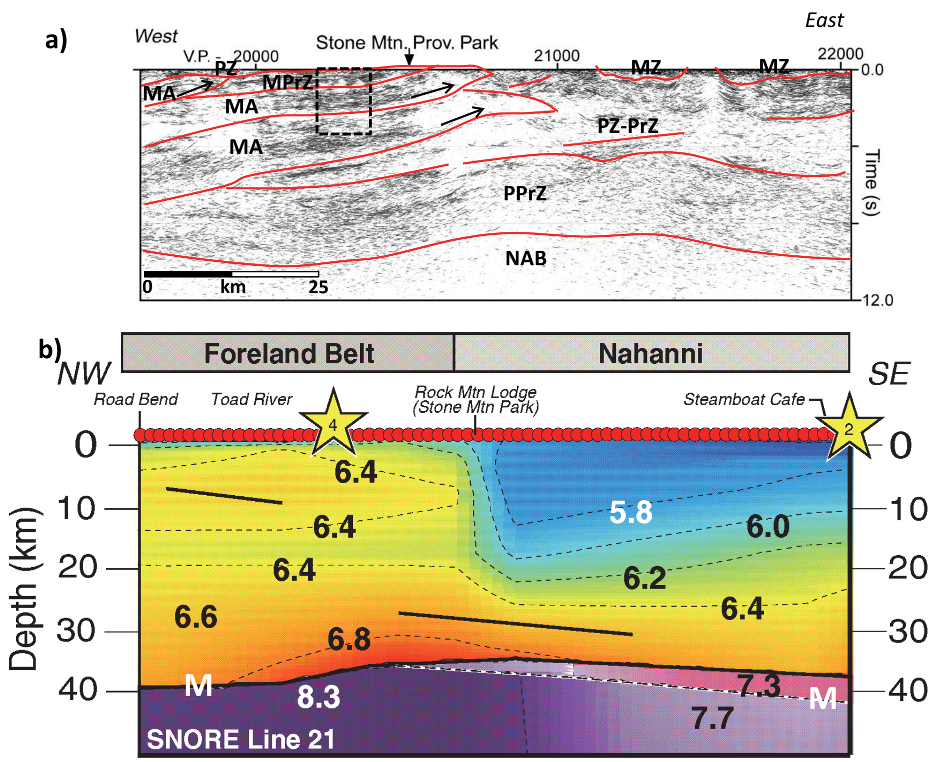

Figure 8. *(a)* Seismic reflection image with interpretation for a segment of SNORCLE Line 2b that crosses the Cordilleran deformation front (location in Fig. 5). VP refers to vibration point (station) locations. Abbreviations for geological units are: MA, Paleoproterozoic Muskwa assemblage (1.8–1.2 Ga); MPrZ, Mesoproterozoic (1.2–0.8 Ga); MZ, Mesozoic; NAB, North American basement (>1.8 Ga); PPrZ, Paleoproterozoic (<1.8 Ga); PrZ, Proterozoic; PZ, Paleozoic. Arrows show sense of thrusting of Paleoproterozoic Muskwa assemblage over and into Paleozoic and younger Proterozoic rocks. Dashed rectangle is the location of the field data shown in Figure 9. *(b)* Refraction velocity model for the same part of Line 2b as illustrated in (a). Yellow stars show shot point locations as identified in Figure 5. Red circles are recording station locations. Dashed lines are velocity contours labeled in km/s. Solid black lines identify regions from which wide-angle reflections were recorded. M, Moho.

Noting that exposures of Precambrian strata provide an opportunity to tie regionally extensive reflections to geological outcrop, Cook and Siegel (2006) generated synthetic seismograms for comparison with field observations. They took measured layer thicknesses and lithologies from prior field work, estimated layer densities and velocities from the literature, calculated reflection coefficients for layer boundaries and convolved these results with a zero-phase wavelet to generate a suite of synthetic seismograms representative of the lithological layering (Fig. 9a). Reflection features in the synthetic seismogram can be readily correlated with the stratigraphic assemblages. In general terms, three zones of prominent reflectivity are identified: 1) at the base of the Aida; 2) the top of the Henry Creek; and 3) the Tetsa-Chischa interval (Fig. 9a). In Figure 9b, the synthetic traces corresponding to the preferred model (column 2 in Fig. 9a) of Cook and Siegel (2006) are superimposed on one part of the observed seismic section along Line 2b. Prominent reflections in the subsurface can be tied to layers of the Muskwa assemblage that outcrop along the seismic line about 10 km further east and also can be carried deeper to the west. This provides strong evidence for the interpretation of Muskwa assemblage rocks extending for long distances to the west (up to 100 km) and to significant depths (at least 12–15 km) on Line 2b. As noted by Cook and Siegel (2006), two important implications from this study are that the known Muskwa assemblage thickens dramatically westward and that the Muskwa strata were deposited in a westward-deepening basin analogous to, and probably correlative with, the Fort Simpson basin, which was identified on SNORCLE Line 1 located about 250 km to the north.

Velocity models from a refraction survey along the same line provide further evidence for the interpretation of Muskwa assemblage rocks thrust up toward the surface and for the basin (Welford et al. 2001). Figure 8b shows a segment of the velocity model corresponding to the same region as that of Figure 8a. Two prominent features in the mid-to-upper crust are significant for this discussion. The first is the

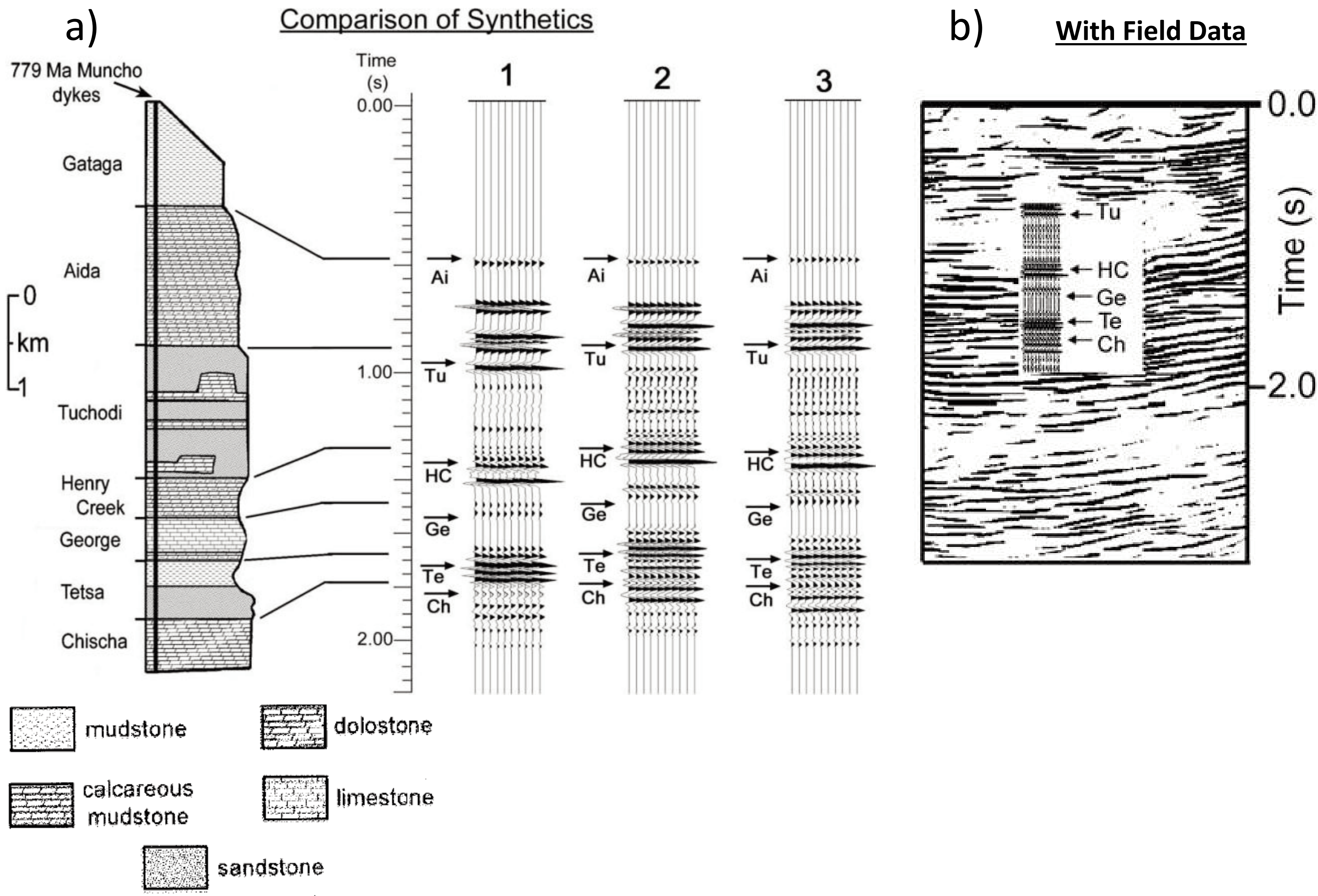

Figure 9. *(a)* Correlation of the generalized stratigraphy of the Muskwa assemblage to three synthetic seismic traces calculated for three differing velocity–density relationships for the units in the stratigraphic column (Cook and Siegel 2006). Synthetic 1 used values that maximized the differences between high and low values; synthetic 3 used values that minimized these differences. Synthetic 2 is the preferred model and used velocity and density values that are near the higher end of published values. *(b)* Comparison of synthetic model 2 with a part of the observed reflection section from the interpreted Muskwa assemblage (section located in Fig. 8a). From Cook and Siegel (2006).

westward thickening package of low upper crustal velocities (≤ 6.2 km/s) extending to 20 km depth in a region east of the craton-Cordillera boundary. Based on drillhole information, the upper ~2.5 km represent Phanerozoic sedimentary rocks of the Western Canada Sedimentary Basin, but the remaining 15 km or so are probably associated with Proterozoic to Paleozoic sedimentary rocks of the Fort Simpson basin. The second feature is the high velocity material (~6.4 km/s) extending from near surface to about 20 km depth below the Foreland belt. Rocks with such velocities are normally found at mid-crustal depths so their presence near the surface is consistent with upthrust Paleoproterozoic Muskwa assemblage rocks as interpreted on the reflection section.

APPALACHIAN OROGEN OF SOUTHERN NEWFOUNDLAND

From the perspective of Lithoprobe, the Appalachian orogen of Newfoundland and the surrounding continental margin presented an opportunity to study the mechanisms and consequences of ocean opening and closure. An ancient ocean, Iapetus, opened during the early Paleozoic. Its closure brought Laurentia, an amalgamated continent, together with Avalonia, a microcontinent that had rifted from the margin of Gondwana, another amalgamated continent to the east, in the Late Cambrian or Early Ordovician. Strike-slip faulting in the Carboniferous created pull-apart basins; extension due to the opening of the Atlantic Ocean in the Triassic to Jurassic overprinted Appalachian structures in areas surrounding the island. Excellent rock exposures in Newfoundland and data from many exploratory wells on the Grand Banks record the evolution of the Appalachians and subsequent development of the rifted Atlantic margin. Williams (1979, 1995) provided a good summary of the geology as known at those times.

As shown on a geological map of Newfoundland (Fig. 10; Colman-Sadd et al. 1990), the lower Paleozoic Humber margin formed on the Mesoproterozoic basement of Laurentia, a part of which (the Humber Arm allochthon, HAA) was emplaced during Early Ordovician (~480 Ma) orogenesis. Immediately east of the Humber zone, and juxtaposed to it along the Cabot fault–Baie Verte Line (CF-BVL) fault system, lies the Dunnage zone, which consists of remnants of oceanic basement, cover and intervening volcanic arcs and backarcs from the Iapetus ocean and surrounding regions. The Dunnage zone is divided into two subzones, the Notre Dame–Dashwoods that has peri-Laurentian affinities and the Exploits that has peri-Gondwanan affinities. During the early Late Ordovician (about 455 Ma), the two subzones were juxtaposed along the Red Indian Line (RIL). The Annieopsquotch accretionary tract within the Notre Dame–Dashwoods subzone represents oceanic terranes of a suprasubduction zone. The Gander zone, composed mainly of metasedimentary rocks derived from the Gondwanan continental margin, lies to the east of the Exploits subzone, but the two are intimately connected. Several windows of Gander zone rocks occur

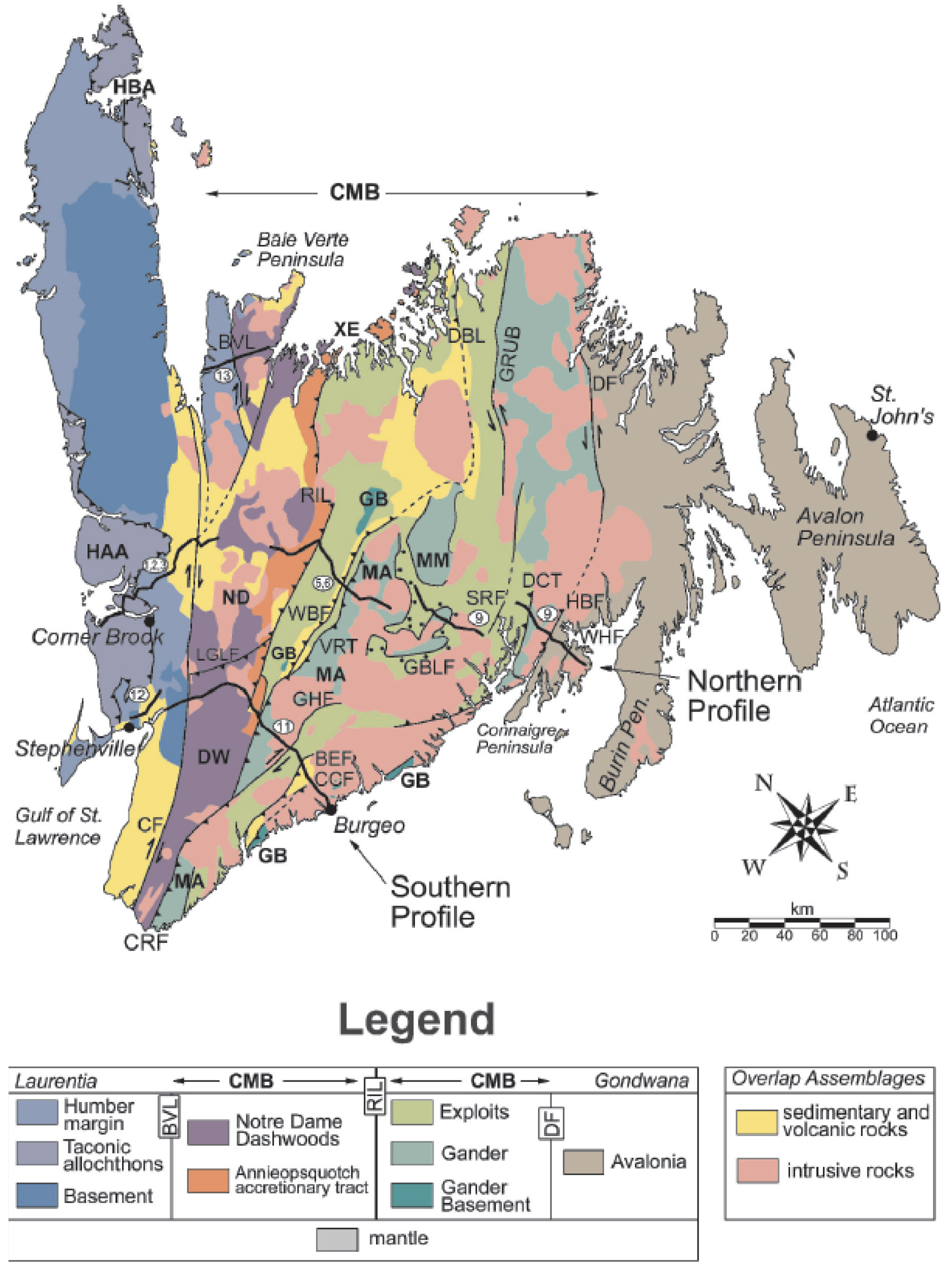

Figure 10. Simplified geological map of Newfoundland showing locations of Lithoprobe's northern (lines 1 to 9) and southern (lines 12 and 11) profiles (general location 5 in Fig. 1). Abbreviations are given in Table 1; some are not referenced. From van der Velden et al. (2004), after Colman-Sadd et al. (1990).

Table 1. Abbreviations for Newfoundland geological map and cross-section (Figures 10 and 11).

AAT	Annieopsquotch accretionary tract	HAA	Humber Arm allochthon
BEF	Bay d'Est fault	HBA	Hare Bay allochthon
BVL	Baie Verte line	HBF	Hermitage Bay fault
CCF	Cinq Cerf fault	IHT	Indian Head thrust
CF	Cabot fault	LGLF	Little Grand Lake fault
CMB	Central Mobile belt	LRF	Lloyds River fault
CRF	Cape Ray fault	M2'	Mantle reflections
DBL	Dog Bay line	MA	Meelpaeg allochthon
DCT	Day Cove thrust	MM	Mount McCormack window
DF	Dover fault	ND	Notre Dame domain
DW	Dashwoods domain	RIL	Red Indian line
GB	Ganderian basement	SC'	Subduction complex
GBLF	Great Burnt Lake fault	SRF	Salmon River fault
GHF	Gunflap Hills fault	VRT	Victoria River thrust
GLC	Ganderian lower crustal reflections	WBF	Woodbrook fault
GLT	Grand Lake thrust	WHF	White Horse fault
GRUB	Gander River ultrabasic belt	XE	Xenolith locality

within the Exploits subzone, indicating that the latter is allochthonous. The easternmost part of Newfoundland comprises the Avalon zone, or Avalonia, which was likely part of Gondwana for at least part of its history. Avalonia includes a late Precambrian volcanic and sedimentary sequence overlain by Cambrian to Early Ordovician sedimentary rocks, the latter of which are only mildly deformed and metamorphosed in contrast with rocks of equivalent age in the Dunnage zone. Note that the Central Mobile belt, comprising the Dunnage and Gander zones, decreases in width from about 200 km in north-central Newfoundland to about 50 km in southwestern Newfoundland.

In 1989, Lithoprobe recorded about 650 km of crustal reflection data, mainly along two profiles, northern and southern (Fig. 10), each consisting of a number of individual lines, plus one short line across the Baie Verte peninsula. Accessing available roads, the northern profile crossed the wide part of the Central Mobile belt and the southern one crossed the narrower part. Quinlan et al. (1992) presented an initial interpretation of the contractor-processed data set and Hall et al. (1998) included a more comprehensive interpretation that also considered the wide-angle reflection/refraction and potential field studies that were carried out. The data quality for these interpretations was not particularly good. van der Velden et al. (2004) reprocessed the two main profiles to provide a much better image of the crustal structure of the Newfoundland Appalachians and hence a revised and improved interpretation.

Figure 11 shows the interpretation of van der Velden et al. (2004) superimposed on the seismic data section for the southern profile (lines 12 and 11; locations on Fig. 10). The interpretation is consistent with the known geology and is their preferred one but, as clearly expressed by van der Velden et al. (2004), other alternatives exist, particularly when some seismic features are considered in detail. For this discussion, I will focus only on a few of the major features shown in the interpretation without including explanations of alternatives. Starting on the western side near Stephenville and extending eastward to the Cabot fault-Baie Verte Line (CF-BVL), most of the crust comprises Laurentia. Reflectivity is east-dipping and associated with thrust faults to at least 4 s. Two of these are identified as the Indian Head thrust (IHT) and the Grand Lake thrust (GLT). The former carries the Indian Head inlier, a slice of Proterozoic basement. The latter carries the Steel Mountain anorthosite, another piece of Proterozoic basement.

The CF-BVL represents the eastern boundary of Laurentia at the surface and, on the basis of cut-offs of the chaotic reflectivity (C) in the upper crust to the east and of the east-dipping reflectivity in the lower crust of Laurentia to the west, is shown as near-vertical. van der Velden et al. (2004) pointed out that the BVL is an old fault line that was likely reactivated with the CF as a dextral transcurrent fault. The lower crustal area (A') and a similar region on the northern profile probably mark the easternmost extent of Laurentia in the lower crust. Both the Lloyds River fault (LRF) and Red Indian Line (RIL) dip westward and between them carry the Annieopsquotch accretionary tract (AAT) over which the Notre Dame–Dashwoods was thrust. The latter interpretation for the RIL is markedly different from that in an earlier publication that had the RIL dipping southeast (Hall et al. 1998). East of the RIL, the high-grade rocks of the Meelpaeg allochthon were placed over the lower-grade rocks of the Red Cross group of the Exploits domain (reflectivity F) along the Victoria River thrust. The dextral Gun Hills fault cuts the Meelpaeg allochthon. The south-dipping Bay d'Est fault carries Silurian sedimentary and volcanic rocks of the La Poile basin in its hanging wall. Exposures of Ganderian basement complete the profile to the east.

The most prominent reflectivity on the profile is in the lower crust on the eastern third of the line. This reflectivity (GLC for Ganderian lower crust) cannot be tied directly to surface exposures but is interpreted as representing transposed compositional layering within Neoproterozoic–Cambrian arc rocks that form the basement to the Gander Group. They are shown as projecting into the mantle, based mainly on similar but clearer reflectivity on the northern profile. van der Velden et al. (2004) suggested that this may represent a fossil subduction zone that accommodated convergence between Laurentia and Ganderia. In this interpretation, H' would represent a thrust surface and SC' would be associated with a subduction complex (Fig. 11).

WESTERN MARGIN OF NEWFOUNDLAND – A CLOSER LOOK

Whereas the previous section and Figure 11 depict a crustal-scale interpretation, often the same seismic data can be used for much more detailed studies of specific geological features. Waldron

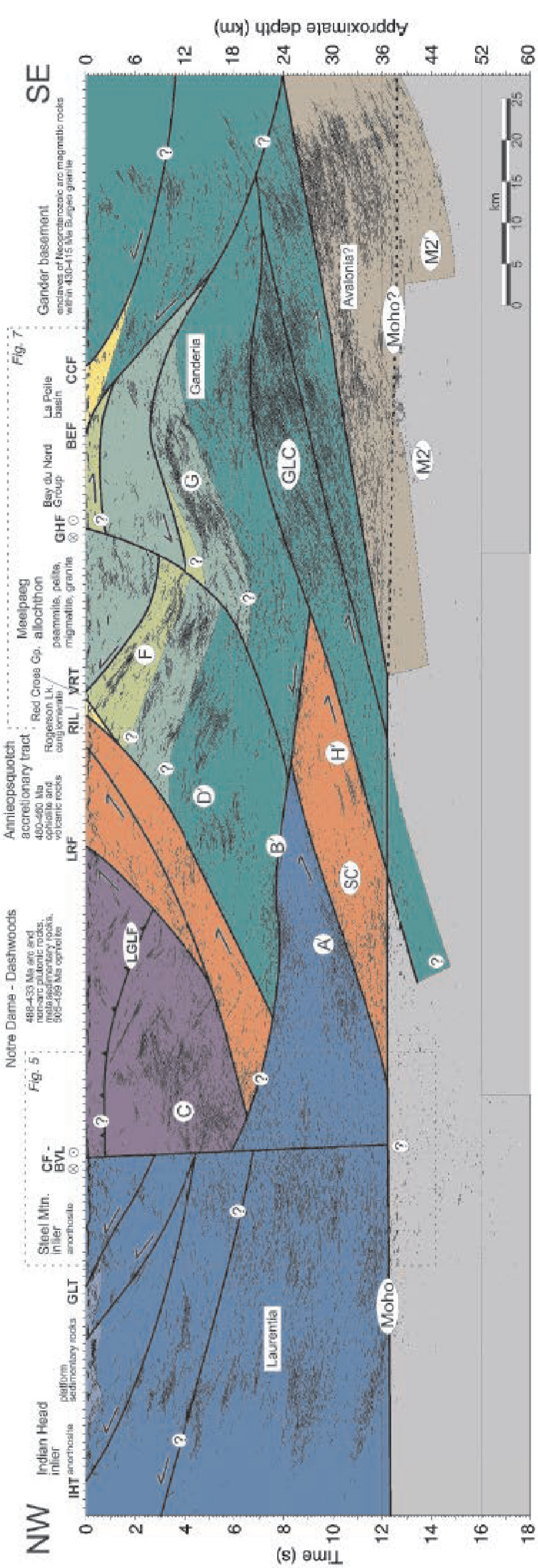

Figure 11. Interpretation of the southern profile (lines 12 and 11) overlain on migrated seismic reflection data. Presentation is 1:1 based on the assumption of an average crustal velocity of 6.0 km/s. Abbreviations are given in Table 1. A', B', C, D', F and G are features discussed in the text. From van der Velden et al. (2004).

et al. (1998) considered reprocessed Lithoprobe lines 89-1, -2, -3, -12 and -13, recorded in the western margin of Newfoundland (Fig. 10), within the context of new (at the time) stratigraphic and isotope data generated through Lithoprobe studies and industry seismic and drilling results that were released in the public domain. With this information, they provided a revised interpretation of the seismic data consistent with stratigraphic and structural relationships observed in field studies and the industry subsurface data. In a complementary study, Stockmal et al. (1998) combined new industry reflection data, both onshore and offshore, in and adjacent to the Humber zone to provide a revised interpretation of the structural style and timing of deformation at the Appalachian front. These studies and earlier ones referenced within them led to a resurgence of exploration in western Newfoundland, including industry seismic and drilling. One or more small economic deposits were found and production from these has been carried out.

To illustrate the combination of geology and geophysics as they apply to the interpretations by Waldron et al. (1998), I have selected Line 89-12 and its extension west to the offshore region, which is based on industry seismic data and drillhole information (Fig. 12). Line 89-12 was recorded mainly on Quaternary and Carboniferous cover rocks but exposures to the north indicate that Cambrian–Ordovician carbonate rocks (platform succession) underlie the cover rocks. Most of the upper crust is interpreted to be associated with Grenvillian basement, which occurs as a distinct massif in the Indian Head Range (Fig. 12a), and rift-related rocks of Proterozoic age. Prominent reflections A, B and C in Figure 12b are inferred to be intra-basement features but details are not available because they do not come close to the surface. For reflection A, this is an important inference because an earlier interpretation had it representing platform units continuous beneath an allochthonous Port au Port–Table Mountain block (Waldron and Stockmal 1994).

Based on geological outcrops north and west of the seismic line,

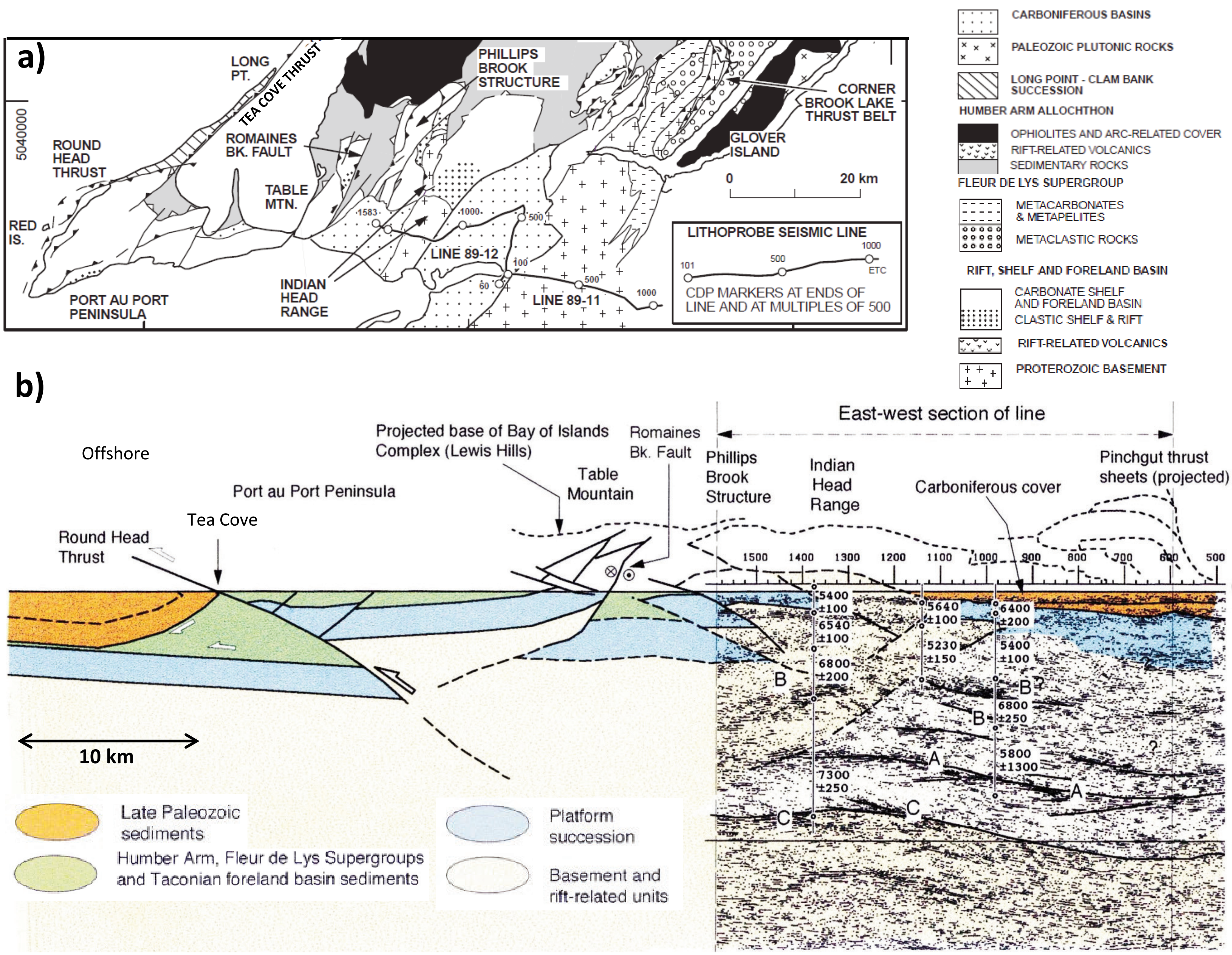

Figure 12. *(a)* Geological map of part of southwestern Newfoundland showing the location of Lithoprobe seismic reflection Line 89-12 (also see Fig. 10 for location; general location 5 on Fig. 1). Map adapted from Waldron et al. (1998). *(b)* Interpretation of Line 89-12 extended westward to the offshore based on information from industry seismic and drillholes. Numbers at the top of the seismic section are common-depth-point (CDP) markers; numbers between dots on the vertical lines are interval velocities and estimated errors in metres per second as derived from velocity analyses applied to the seismic data. A, B and C are features mentioned in the discussion. From Waldron et al. (1998).

reverse faults are the dominant structural features. They cut the carbonate-cored massifs as shown around the join of the seismic section with the interpretation extending to the west (Fig. 12). For example, a thrust at the western edge of the Phillips Brook structure places Paleozoic platform carbonate rocks over rocks of the Humber Arm allochthon. Similarly, a little to the east, Grenvillian basement rocks are thrust over the Paleozoic carbonate rocks. The Romaines Brook fault, a west-dipping feature that shows reverse slip overprinted by dextral strike-slip motion, bounds the eastern edge of the structural block that underlies the Port au Port Peninsula. The structure around the Table Mountain area resembles a positive flower structure and may be associated with inversion of an earlier extensional basin. The well-known Bay of Islands ophiolite complex, interpreted as oceanic lithosphere formed in an arc setting, is exposed northeast of Table Mountain. The base of this complex is projected to the region of the cross-section (Fig. 12). Uplift of the blocks bounded by the reverse faults brought deeper, autochthonous and parautochthonous rocks to the surface. Erosion has removed any detached platform sheets and most of the Humber Arm allochthon, including the Bay of Islands complex. On the western edge of the Port au Port Peninsula, the Round Head thrust separates the Humber Arm allochthon and associated rocks from the offshore late Paleozoic sedimentary rocks. The thrust was a normal fault during formation of a Taconian foreland basin but now shows net reverse separation of several kilometres, at depth placing Grenvillian basement above platform succession and Humber Arm rocks. Below the Round Head thrust, a structural triangle zone of Humber rocks has been formed. Based on seismic data further north, this triangle zone extends for at least 100 km along the coastline.

GRENVILLE PROVINCE IN SOUTHWEST QUEBEC

The Grenville Province is the primary exposure of the late Proterozoic to early Neoproterozoic Grenville orogen, one of the greatest collisional belts ever formed on Earth. The orogen extends from Texas in the southwest to the Labrador Sea in the northeast (Fig. 1). Lithoprobe focused on the Canadian part of the orogen, which exposes mainly crystalline rocks that were deformed and metamorphosed at lower to mid-crustal depths in the west, and middle to upper crustal depths in the east. The Grenville Front is the boundary between the Grenville Province and the older structural provinces comprising the Laurentian cratonic collage to the northwest (Fig. 1; Wynne-Edwards 1972). At the crustal scale, the Grenville Front is a sharp, northeast-trending tectonic break that is well defined on regional gravity and magnetic maps (e.g. Ludden and Hynes 2000). It marks the northwestern limit of tectonic reworking of rocks of the older provinces during the Grenvillian orogeny, a complex series of tectonic events that took place between 1250 and 980 Ma. From a mountain-building perspective, orogenesis started at ca. 1245 Ma in the southwest region but not until ca. 1090 Ma in the northeast region. As a consequence, crustal cross-sections along the province show considerable variation from southwest to northeast (e.g. Rivers et al. 2012).

From a geological perspective, the Grenville Province can be divided into two major belts, parautochthonous and allochthonous, which are subdivided into a series of terranes or domains (e.g. Davidson 1986; Rivers et al. 1989). The parautochthonous belt includes terranes or domains that, although strongly deformed, were not transported far from their pre-Grenvillian location or greatly separated from their basement. The allochthonous belt includes terranes or domains in the interior or hinterland of the Grenville Province that are detached from their basement and are inferred to have been substantially displaced during the Grenville orogeny. The Allochthon Boundary thrust separates the two major belts (e.g. Rivers et al. 2012).

Lithoprobe ran a number of seismic reflection and refraction lines across the Grenville Province, mainly in the southwest but including one in the central Grenville (see next section) and some studies onshore and offshore of Labrador. Figure 13a shows the location of one of the main seismic reflection surveys (lines 52 to 54) across the southwestern Grenville, northwest of Montreal, recorded in 1993; Figure 13b shows the seismic data and its interpretation. To extend the cross section northward across the Grenville Front (Fig. 13b), I have added lines 15, 16 and 16A, which were recorded in 1991 and are offset about 150 km west from Line 52, mainly along strike (Fig. 13a).

Lines 16A, 16 and 15 were shot across the Pontiac metasedimentary belt, an Archean sub-province of the Superior Province, the Grenville Front zone and into the Archean parautochthon of the Grenville Province. The metasedimentary rocks comprise mainly metawacke and several suites of plutonic rocks and are dated as being < 2686 Ma (Davis et al. 1994). Calvert and Ludden (1999) described the geology and the interpretation of the three seismic lines within the sub-province. They interpreted the wedge of north-dipping reflections below lines 16A and 16 that terminate below Line 15 as a relict accretionary wedge, which grew southward by the underthrusting of younger sedimentary rocks. The southern half of Line 15 shows southeast-dipping reflectivity, which terminates sub-horizontal reflectivity beneath it and to the northwest that represents the Pontiac metasedimentary belt. The base of this reflectivity can be projected to the surface exposure of the Grenville Front and thus indicates the Grenville being thrust upon the older Archean rocks.

Martignole and Calvert (1996) summarized the geology and provided an interpretation of lines 52 to 54 within the Grenville Province. Line 52 begins south of the Grenville Front (Fig. 13a) but southeast-dipping reflectivity in the mid-to-lower crust is associated with the Grenville Front zone (GFZ) and the base of the reflectivity is interpreted to be the Grenville Front (GF, Fig. 13b). The discontinuous, SE-dipping reflections in the GFZ are inferred to be associated with two events, NW-directed thrusting at about 1 Ga followed by subsequent SE-directed extension. The Grenvillian thrusting created overthickened crust that was likely thinned by extension along low-angle, SE-dipping shear zones, thus forming the present Moho

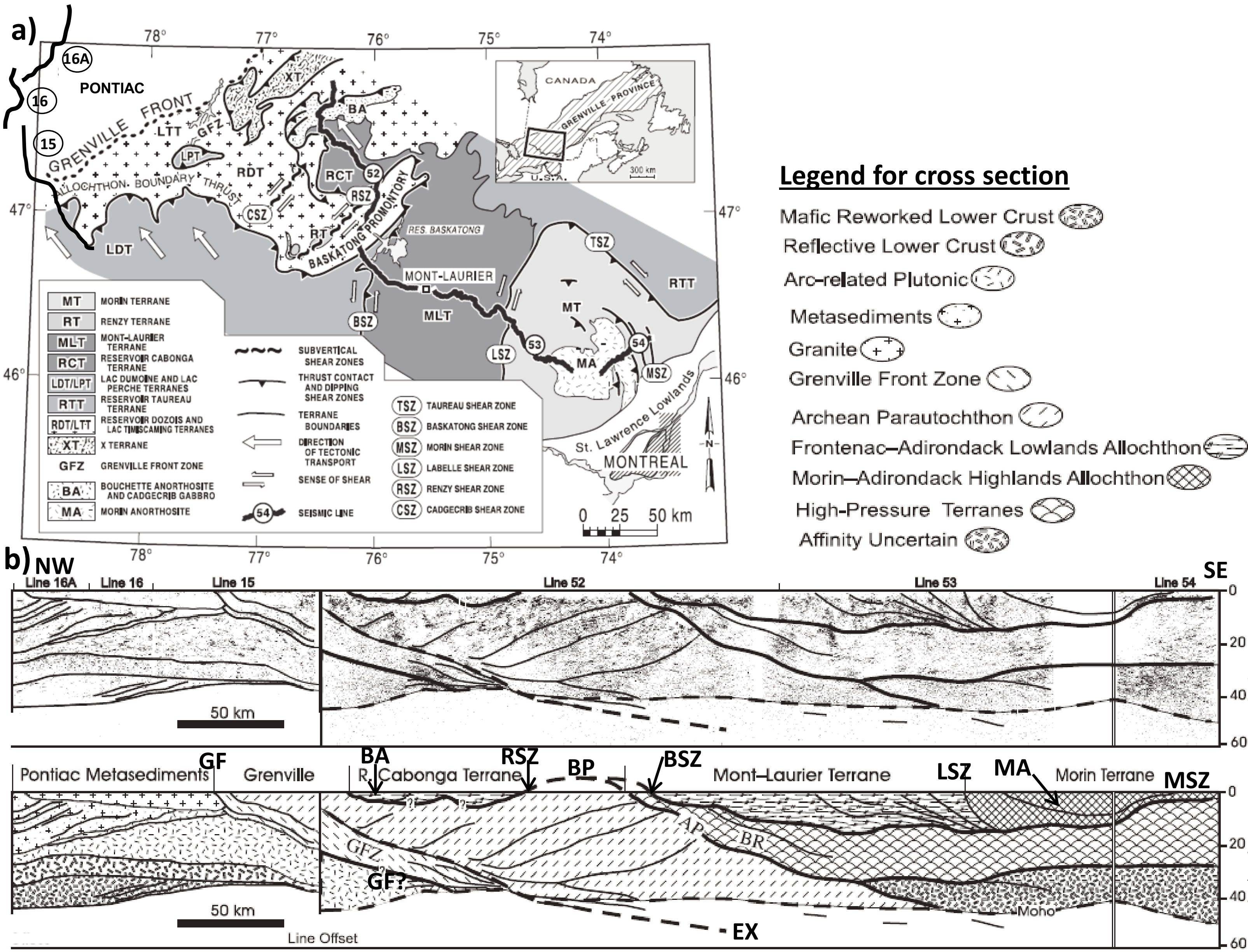

Figure 13. *(a)* Structural map of the Grenville Province in western Quebec (see inset for location; general location 6 on Fig. 1). Lithoprobe seismic reflection profiles16A, 16, 15 and 52 to 54 are indicated by the thick black lines. (Adapted from Martignole et al. 2000). *(b)* Upper panel: composite time-migrated seismic reflection section with interpretive lines superimposed; depth scale is approximate. Lower panel: geological interpretation of the seismic section; legend is shown in the upper right of the figure. Abbreviations given in the legend for (a). Additional abbreviations: AP, Archean-Proterozoic boundary; BP, Baskatong promontory; BR, Baskatong ramp; EX, possible reactivation in extension of the major crustal thrusts in the Grenville Front zone; GF, Grenville Front. From Ludden and Hynes (2000); based on results from Martignole and Calvert (1996) and Calvert and Ludden (1999).

that is thinnest at the base of the GFZ (Fig. 13b). Most of the crust above and to the southeast of the GFZ shows NW-dipping reflections associated with the migmatitic Archean parautochthon. Farther to the southeast, these reflections are truncated by another set of SE-dipping reflections, which are interpreted as the Baskatong crustal ramp (BR). The base of the ramp represents the Archean–Proterozoic boundary (AP) and thus the base of the allochthonous terranes of the Grenville Province, the Allochthon Boundary thrust. Situated above the Baskatong ramp, the allochthonous Mont Laurier terrane, a zone with prominent SE-dipping reflectivity, was thrust over the ramp along the Baskatong shear zone (BSZ). Farther to the north near the start of Line 52, an equivalent rock unit, the Reservoir Cabonga terrane, shows as a thin layer (up to 5 km thick) above the Archean parautochthon. The Labelle shear zone is the southeastern boundary of the Mont Laurier terrane and is interpreted as a transcurrent fault that is truncated at depth by the Baskatong shear zone. The southeast parts of Line 53 and Line 54 show a synformal feature in the upper crust with limited reflectivity that equates with the Morin terrane and, within that terrane, the Morin anorthosite.

In summary, the Grenville Front zone plus ramp anticlines and the overriding basal thrust of the upper crustal allochthons demonstrate the NW-directed propagation of tectonic transport during the Grenvillian orogeny (Fig. 14). The GFZ extends southeast from its surface exposure to the base of the crust and possibly into the lithospheric mantle. To the southeast in the middle to upper crust, deformation and displacement occurred also along the Baskatong ramp (Reservoir Baskatong terrane in Fig. 14). These two crustal discontinuities also accommodated most of the post-collisional extension, causing a thinning of the crust immediately southeast of the Grenville Front and affecting the crust up to 350 km away from the front.

GRENVILLE PROVINCE IN EASTERN QUEBEC

In the central Grenville Province in eastern Quebec, the Manicouagan Imbricate Zone (MIZ) is structurally sandwiched between the parautochthonous and autochthonous belts (Figure 15a). It comprises the parautochthonous Lelukuau and Tshenukutish terranes, the latter of which in the southwest is divided into the Southwest and Island domains. The MIZ includes widespread exposures of high pressure granulite and subordinate eclogite-facies rocks, indicating that these rocks were formerly deeply buried (Indares et al. 2000). During the Triassic, a meteorite crashed into the region, resulting in the formation of a circular structure that encompasses the Manicouagan reservoir and an interior island that is primarily covered by Triassic volcanic rocks. While underlying Precambrian rocks on the island show evidence of the impact, similar rocks on the outer margin of the reservoir show little evidence of it. Indeed, geological exposures around the outer margin are excellent and provided extensive geological data that can be related to a Lithoprobe seismic profile (e.g. Hynes and Eaton 1999; Indares et al. 2000).

Lithoprobe Line 55 runs for 250 km along highway 389, the only road in the region, to the southeast of the Manicouagan reservoir (Figure 15a). The ideal seismic line would run NNW-SSE, approximately coincident with the cross-section line A-A' of Figure 15a. However, the geological features to the northwest of the seismic line dip southeast and, as a result, Line 55 images geological structures at depth that outcrop to the northwest. This fortunate circumstance has resulted in a number of publications that relate to the three-dimensional crustal structure and evolution of the region. Eaton et al. (1995) discussed north-to-south crustal thinning based on Moho reflections that decrease from about 50 km (16 s, two-way travel time) to 40 km (13 s) and demonstrate that prominent upper crustal reflections can be correlated with exposures of eclogite-facies rocks in the MIZ. Furthermore,

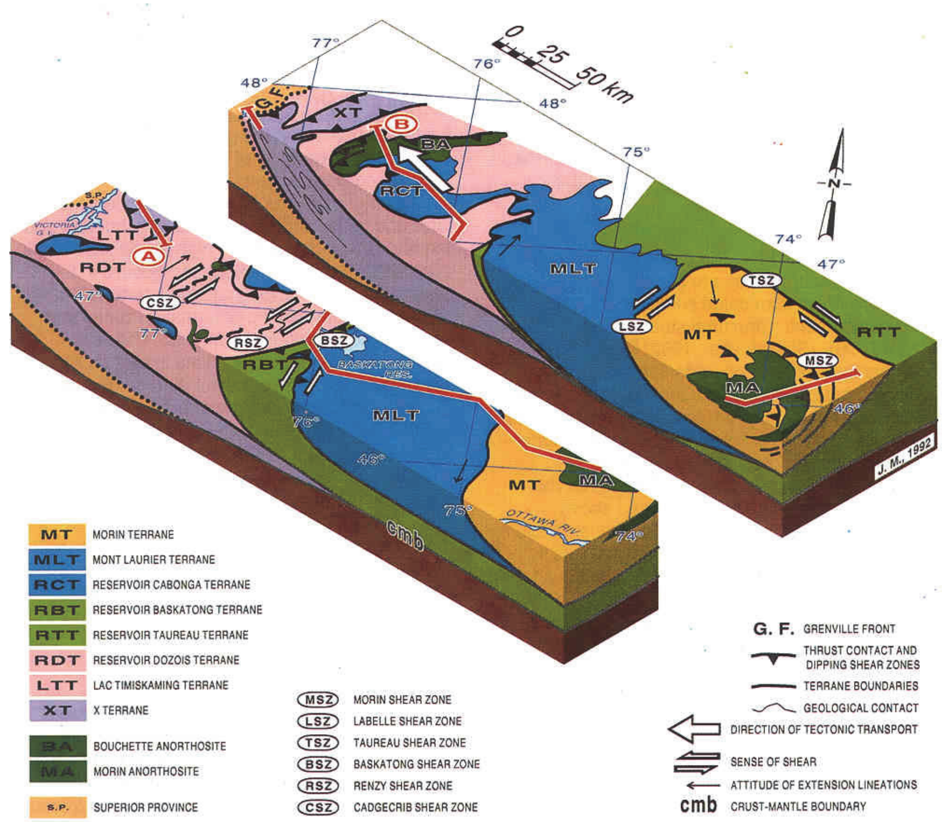

Figure 14. Three-dimensional interpretation of geological structures in the Grenville Province of western Quebec based on geological studies and interpretation of seismic data along lines 52, 53 and 54 (thick, red lines). Illustration provided by J. Martignole (personal communication).

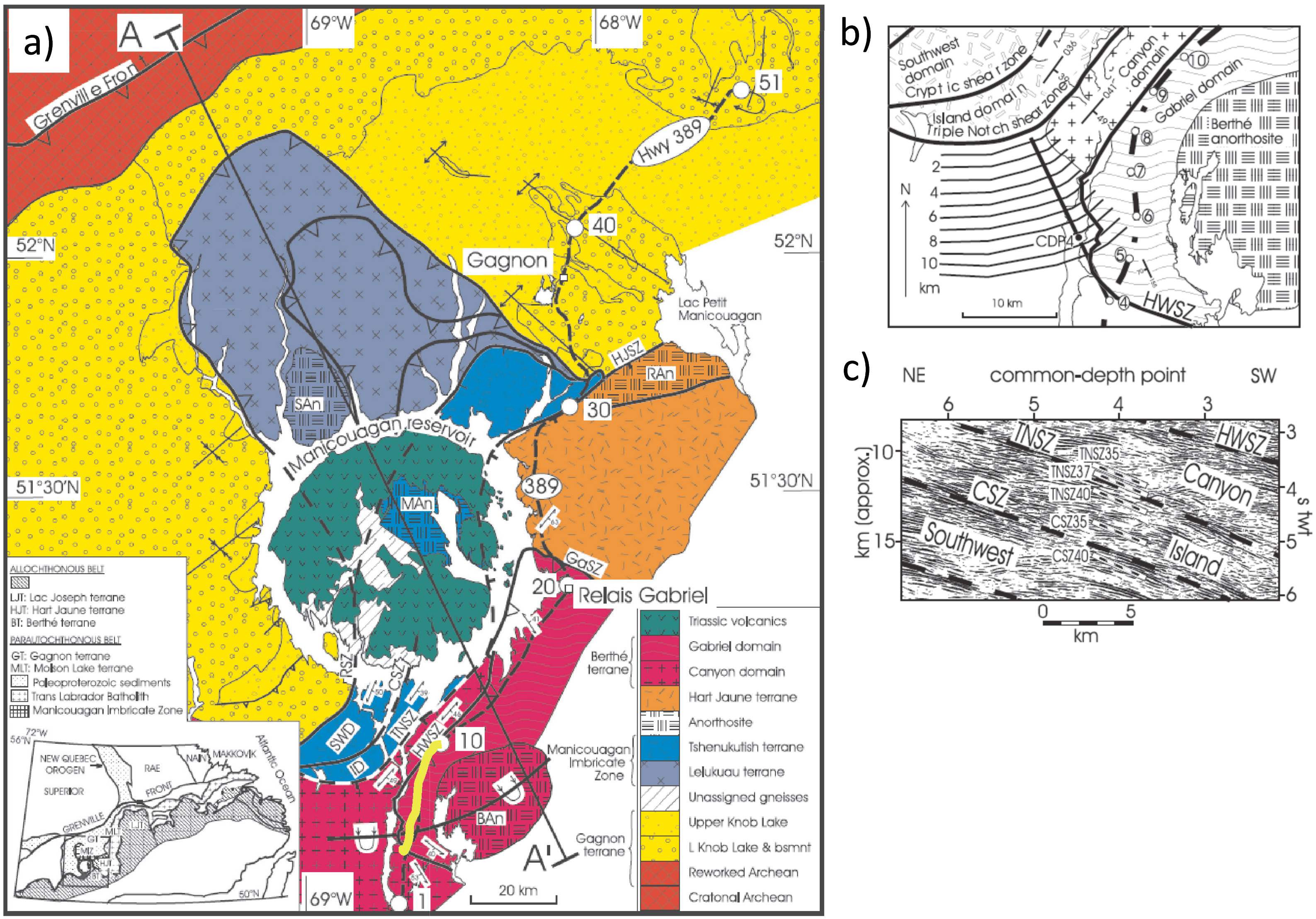

Figure 15. *(a)* Geological map of the Manicouagan region (location 7 in Fig. 1) in the vicinity of seismic line 55 recorded along highway 389 (dashed line); white circles with numbers are shot point locations. Heavy solid lines are faults. Yellow line south of '10' identifies shot points 4 to 10, shown in more detail in (b). Map location shown in inset with legend, lower left. Abbreviations: BAn, Berthé anorthosite; CSZ, Cryptic shear zone; GaSZ, Gabriel shear zone; HJSZ, Hart Jaune shear zone; HWSZ, Highway shear zone; ID, Island domain; MAn, Memory Bay anorthosite; RAn, Raudot anorthosite; RSZ, Relay shear zone; SAn, Seignelay anorthosite; SWD, Southwest domain; TNSZ, Triple-Notch shear zone. AA' is location of the section in Figure 16b. *(b)* Surface geology in the region between shot points 4 and 10 (circled numbers). Structural symbols show mean attitudes of gneissic layering. Numbered, evenly spaced solid black lines show structure contours on the Triple-Notch shear zone (TNSZ) in the subsurface. Filled circle labeled 'CDP4' is the position in the subsurface at which the TNSZ is imaged by the seismic data; see (c). *(c)* Unmigrated portion of line 55 near common-depth-point 4. Heavy dashed lines are interpreted trajectories of faults; abbreviations as above. Slanted barber's poles show modelled positions and attitudes of reflectors associated with TNSZ, for dips of 35°, 37° and 40° and strike of 060; and of Cryptic shear zone (CSZ) for dips of 35° and 40° and strike of 060. From Hynes et al. (2000).

the data allow interpretation of extensional faults that penetrate the crust to about 20 km and are probably associated with the unroofing of the eclogite-facies parautochthonous terranes. Hynes and Eaton (1999) expanded on the latter point, identifying a large-scale lateral ramp in the subsurface that provided a channel through which material could flow rapidly to shallow depths.

Hynes and Eaton (1999) and Hynes et al. (2000) showed that the combination of well-constrained geological features that dip into the section of a crooked seismic line can be used to provide a three-dimensional representation of the subsurface structure in the vicinity of the line. They demonstrated that there is good correlation between the attitudes predicted for seismic reflectors from gneissic layering at the surface and the attitudes of the observed reflectors. These data are shown in Figure 15c where the 'barber's poles', labelled TNSZnn and CSZnn, represent expected positions and attitudes of reflectors due to gneissic layering based on studies of the Triple Notch and Cryptic shear zones, shown in more detail in Figure 15b. The barber's poles line up very well with the interpreted trajectories of the two faults. Figure 15b also shows an example of 3-D interpretation. The Triple Notch shear zone is identified by the surface geology and the solid dot labeled CDP4 is the position at which it is imaged on the seismic section. These points enable structure contours on the Triple Notch shear zone in the subsurface (Fig. 15b). Similar results can be derived for other faults, such as the Relay shear zone (Hynes et al. 2000; Fig. 15a). The Relay shear zone underlies the Tshenukutish terrane of the Manicouagan Imbricate zone and the combined Triple Notch–Hart Jaune shear zone (Fig. 15a) represents the overlying boundary. Based on identified seismic reflectors from these shear zones, Hynes et al. (2000) derived an isopach map for the Tshenukutish terrane (Fig. 16a). Note that it is lozenge-shaped, being much thicker in the middle part. See the original paper for more details.

Although the seismic survey was run along Highway 389, which is highly oblique to the strike of many geological figures, the combination of

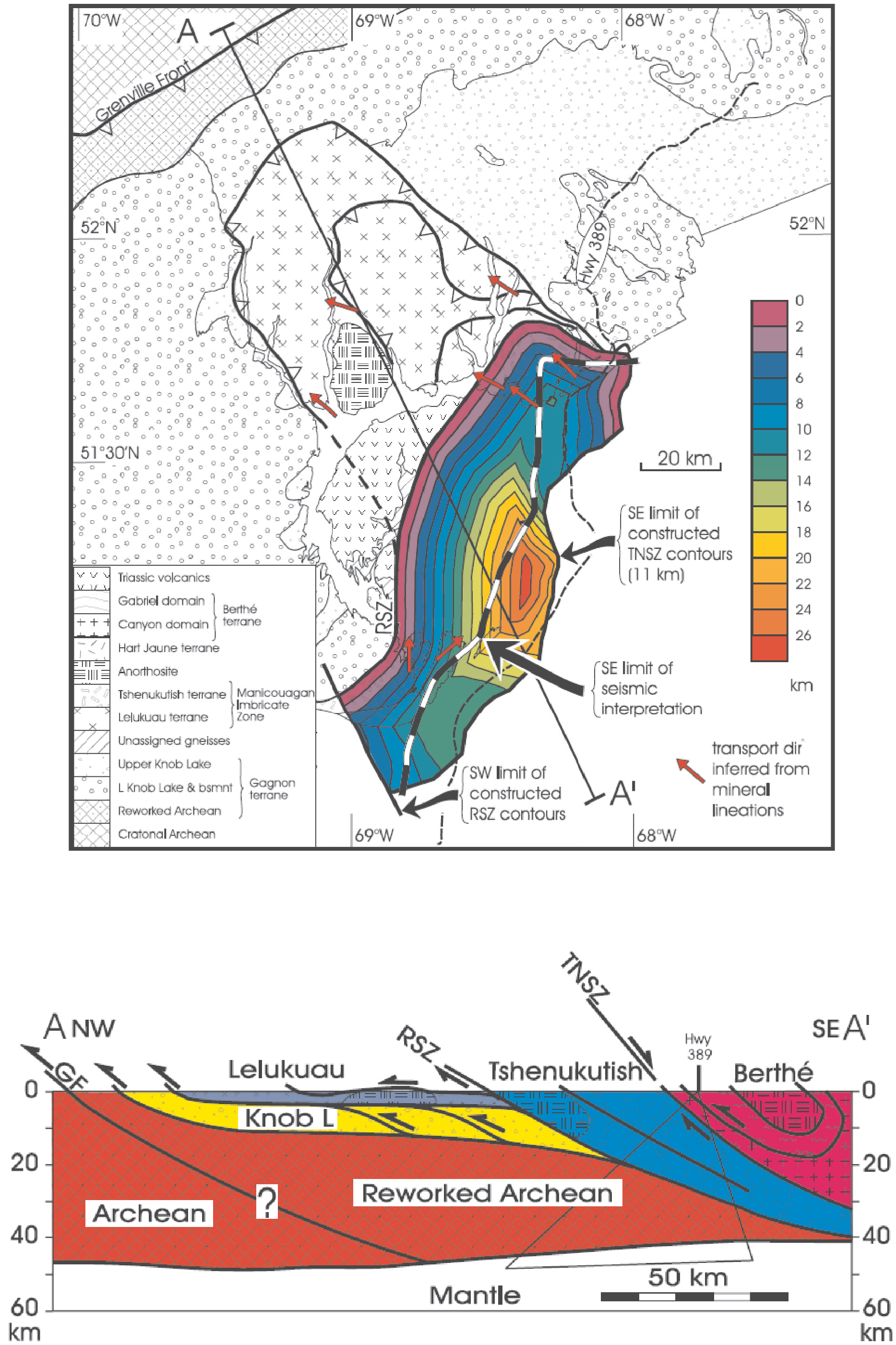

Figure 16. *(a)* Isopach map for the Tshenukutish terrane. Heavy dashed line is the southeastern limit of structure contours for which their position is constrained by observed reflectors. Red arrows show inferred transport directions for rocks within Tshenukutish terrane based on the predominant trends of mineral lineations. AA' is location of section below. *(b)* Vertical cross-section along line AA' (Figs. 15a, 16a). Depths of boundaries within the triangular field beneath the surface trace of Highway 389 are constrained by structure-contour maps derived from interpretation of Line 55. Outside that region, subsurface structure is based on extrapolation parallel to the regional tectonic trend of the Grenville orogen. Colour and ornament same as Figure 15a. From Hynes et al. (2000).

geological studies and seismic interpretation enabled the generation of a vertical cross-section approximately normal to strike (AA' on Figs. 15a and 16a; section in Fig. 16b; Hynes et al. 2000). The section shows the ramp on which the younger rocks were thrust over the Archean rocks of Laurentia and includes the varying thickness of the Tshenukutish terrane of the Manicouagan Imbricate zone along the section as derived from the combined studies. Based on these and related studies, Hynes et al. (2000) developed a model for the tectonic evolution of the northern Grenville Province of eastern Quebec, highlighting the two pulses of crustal thickening associated with the Ottawan phase (1050 Ma) and the Rigolet phase (990 Ma).

GEODYNAMIC MODELLING AND GEOLOGICAL CHARACTERISTICS WITHIN THE SOUTHWESTERN GRENVILLE OROGEN

One of the quantitative approaches being developed by groups around the world to investigate tectonic processes is geodynamical modelling using numerical techniques, through which relationships between the thermo-mechanical properties of the Earth and deformation processes can be addressed. Within Lithoprobe, two components were involved. One was the continuing development of computer simulation capabilities to enable modelling of more realistic and complex processes that have been active in tectonic evolution (e.g. Beaumont et al. 2010; Pysklywec et al. 2010; and references within these papers). The second component was application of geodynamic modelling to fundamental tectonic processes inferred within transects and comparisons of interpreted structures and characteristics with those determined from modelling (e.g. Jamieson et al. 2007, 2010 and references therein). Here, I demonstrate such studies with two examples taken from the work of Jamieson et al. (2010) as they apply to the Grenville orogen.

Homogeneous Himalayan-style channel flow models (Beaumont et al. 2001, 2004, 2006; Jamieson et al. 2004, 2006) were used to investigate the effect of variably strong lower orogenic crust on the evolution of the Grenville orogen, which can be considered a large, hot orogen like the Himalayas. Many parameters are required to adequately describe such models and their evolution with time. However, they can be separated into four key property sets: 1) mechanical, including differing properties for upper, middle and lower crustal layers with the latter comprising blocks with decreasing strength from the exterior of the model to its core where a suture enables subduction; 2) thermal properties associated with the crustal layers; 3) velocity fields and boundary conditions, including a mantle behaviour that is only described kinematically; and 4) properties of surface processes, including erosion but only on the advancing side of the model. Since the lower and middle crust within large, hot orogen models can reach temperatures greater than 700°C, which could generate small amounts of partial melt in felsic rocks, the models also include a parameterized viscosity reduction referred to as 'melt weakening' (Beaumont et al. 2001, 2004; Jamieson et al. 2002).

Within the context of Lithoprobe results for the Grenville orogen, the focus of the modelling is a comparison of model results and data interpretations regarding crustal-scale seismic architecture, regional geology and geochronology, and metamorphic pressure-temperature (*P-T*) data. Some of the specific problems that this focus addresses are the relationships between late, steep orogenic structures at the orogenic flanks and pervasive sub-horizontal structures in the orogenic core; the regionally high metamorphic grade at the present exposure level; and the factors controlling juxtaposition, transport, and exhumation of the different lithotectonic domains.

Figure 17 presents results for a model with specific parameters for the key property sets in which convergence started at 0 Ma elapsed model time (Ma-emt), then stopped at 87 Ma-emt after convergence, Δx, of 1740 km. In order to simulate post-convergent ductile flow, the model was then allowed to run until 112.5 Ma-emt with no further convergence. The latter stage was necessary because constant convergence models did not explain the geologically observed late-orogenic normal-sense shear zones nor consider what happens when convergence is stopped. Note that by 87 Ma-emt, the strong external block F has formed a crustal ramp above which blocks E and D have been thrust and block C is about to join them (Fig. 17a). As a consequence of the cessation of convergence, the hot, weak infrastructure flows outward from the orogenic core towards the foreland, driven by the gravitational potential energy contrast between the plateau and the foreland. This results in thrusting at the flanks of the orogen (Fig. 17b) coincident with ductile extension and thinning in the core. At the interface between the melt-weakened mid-crust and underlying lower crust, normal-sense ductile shear zones develop (Fig. 17b, d). Figure 17c shows the model of Figure 17b with the grid removed and the outline of the Georgian Bay cross-section determined from Lithoprobe studies (Culshaw et al. 1997; White et al. 2000; Jamieson et al. 2007) superimposed. Figure 17e shows the portion of the Georgian Bay cross-section corresponding to Figure 17d. Figure 17c, d and e show that the geodynamic modelling has replicated some of the first-order, crustal-scale architectural features interpreted from Georgian Bay studies.

To extend the comparison beyond that of structural features, Jamieson et al. (2010) compared model *P-T-t* paths from the GO-ST87 model (Fig. 17) with metamorphic *P-T* data and geochronological data from Lithoprobe Georgian Bay studies (Fig. 18). During development of the model, four points that lie within 5 km of the model depth corresponding to the present surface at 112.5 Ma-emt were tracked (Fig. 18c). In Figure 18a, *P-T* data for minerals with ages between 1030 and 990 Ma (Krogh 1994; Bethune and Davidson 1997; Buckley et al. 1997; Corfu and Easton 2001) are compared with maximum temperatures and pressures at those temperatures for model times between 60–90 Ma-emt. The model values cluster within the range of the observational data. When considered in terms of *P-T-t* paths, the four model points show different path styles (Fig. 18b). In the region of the Grenville Front tectonic zone (path 1, upper part of Fig. 18b) and Britt

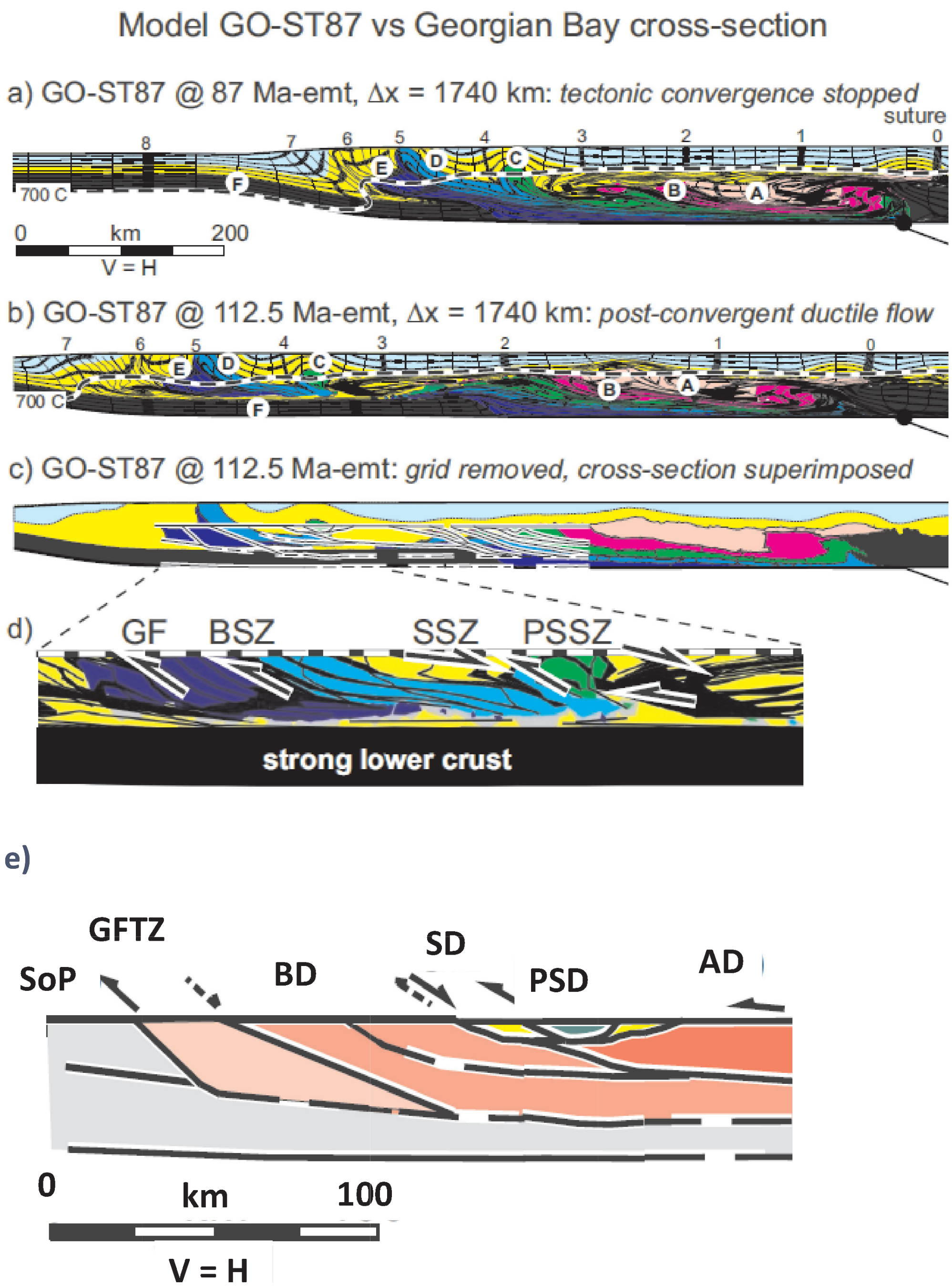

Figure 17. Selected results from Model GO-ST87, in which convergence is stopped at 87 million years elapsed model time (Ma-emt) and post-convergent ductile flow continues afterward. *(a)* Deformed marker grid (distorted rectangular blocks as light lines), crustal blocks (identified by letters in which strength increases progressively from the weakest block, A, to the strongest block, F) and 700°C isotherm (black-white dashed line) at the time convergence is stopped. Numbers correspond to initially vertical markers that were 200 km apart. Strong lower crustal block F has started to underthrust blocks E and D, and is about to underthrust the leading edge of block C, which has already been partially exhumed to mid-crustal levels. *(b)* GO-ST87 at 112.5 Ma-emt, 25.5 Ma after the end of convergence. Note transport of blocks E, D, and C an additional 200 km towards the foreland, accompanied by ductile thinning in the orogenic core. *(c)* GO-ST87 at 112.5 Ma-emt with superimposed outline of Georgian Bay cross-section (determined from other Lithoprobe studies; Culshaw et al. 1997; White et al. 2000; Jamieson et al. 2007). *(d)* Detail of model at 112.5 Ma-emt, truncated at present-day erosion surface (dashed line), showing thrust-sense shear at orogen flanks and normal-sense in melt-weakened mid-crust between blocks D and C. Corresponding geological structures: GF = Grenville Front; BSZ = Boundary shear zone; SSZ = Shawanaga Shear Zone; PSSZ = Parry Sound Shear Zone. *(e)* Georgian Bay cross-section (after Culshaw et al. 1997; White et al. 2000; Jamieson et al. 2007) shown on same scale as model results in (d). Abbreviations: AD, Algonquin domain; BD, Britt domain; GFTZ, Grenville Front tectonic zone; PSD, Parry Sound domain; SD, Shawanaga domain; SoP, Southern province. From figures in Jamieson et al. (2010).

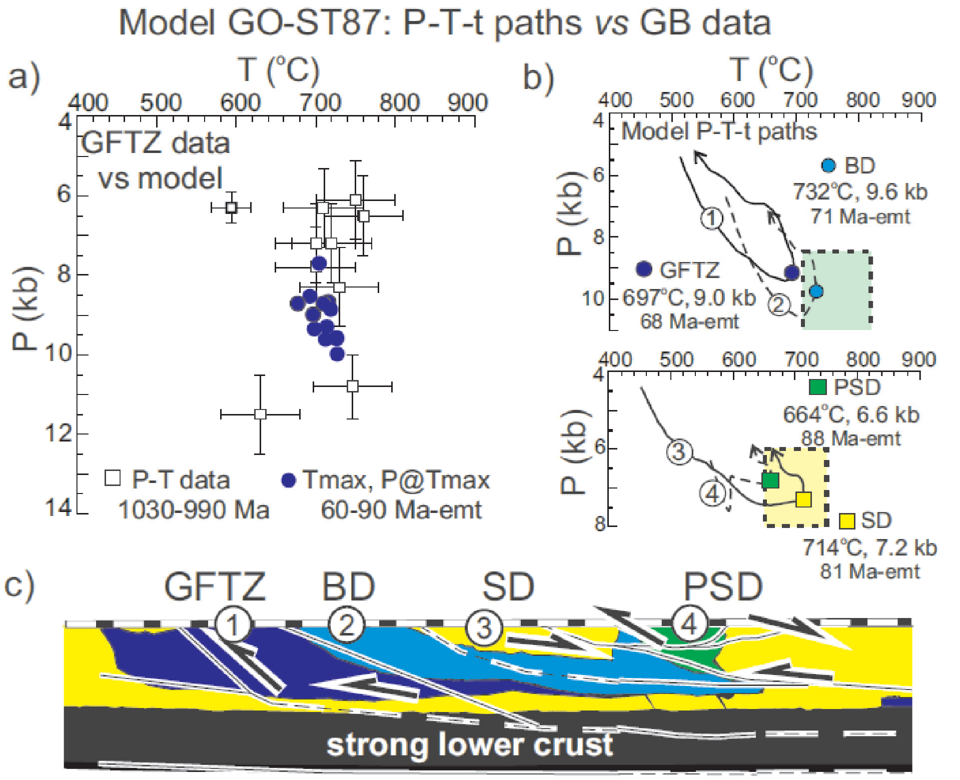

Figure 18. *P-T* results from Model GO-ST87 compared with data from the Georgian Bay transect. *(a) P-T* data from the Grenville Front tectonic zone (GFTZ) compared with model T_{max} and $P@T_{max}$ conditions, which cluster in the mid-range of observations. *(b)* Model *P-T-t* paths from tracked points 1-4 (see part (c)) corresponding to GFTZ (dark blue circle), Britt domain (BD; light blue circle), Shawanaga domain (SD; yellow square), and Parry Sound domain (PSD; green square) respectively. Shaded zones show range of *P-T* estimates for Britt domain (upper panel) and Shawanaga domain (lower panel) respectively (details in Wodicka et al. 2000). GFTZ data shown in panel (a); Ottawan *P-T* conditions for PSD (amphibolite-facies overprint on ca. 1160 Ma granulite) not well constrained. *P-T-t* paths from Model GO-3 are identical up to 87 Ma-emt. *(c)* Model result (grid removed) and cross-section, showing point positions at 112.5 Ma-emt. From Jamieson et al. (2010).

domain (path 2), the paths are tight loops or hairpins representing relatively simple burial and exhumation histories. In the region of the Shawanaga domain (path 3, lower part of Fig. 18b) and Parry Sound domain (path 4), the paths are broad loops with near-isobaric heating portions that indicate prolonged lateral transport beneath the model plateau. The green shaded square and the yellow shaded one show the range of *P-T* data for the Britt and Shawanaga domains (Wodicka et al. 2000), respectively; Grenville Front tectonic zone (GFTZ) data are shown in part a). For all four paths, peak *P-T* points derived from the model study correspond well with the observational data.

THE SASK CRATON IN THE TRANS-HUDSON OROGEN

The Paleoproterozoic Trans-Hudson Orogen (Lewry and Stauffer 1990) is one of Earth's great examples of a preserved collisional belt representing the 'glue' that stuck together older 'bits and pieces' (Archean microcontinents) of North America while simultaneously generating significant volumes of new material (e.g. Ansdell 2005; Corrigan 2012). It extends in an arc from the subsurface in the northern United States south of Saskatchewan and Manitoba, through those provinces to northern Quebec and Baffin Island, then continues eastward as the Rinkian belt and Nagssugtoqidian orogen in Greenland and the Paleoproterozoic collisional belts of the southeastern Churchill Province in Quebec and Labrador. Lithoprobe studies of the Trans-Hudson Orogen (THO) focused on the Saskatchewan–Manitoba segment of the orogen (Fig. 1).

More than 2000 km of crustal seismic reflection data plus other large-scale geophysical surveys and many geological studies were acquired throughout the 500 km-wide internides (Reindeer zone) and across the eastern and western margins of the THO (Hajnal et al. 2005). Based on studies prior to Lithoprobe activities, the THO was considered an example of 'thin-skinned' tectonics in which the Paleoproterozoic rocks observed at the surface were underlain by Archean material, probably the Superior craton, possibly the Hearne craton (see Fig. 1), partly because the Reindeer zone included four small tectonic windows of Archean rocks (Green et al. 1985). However, a high quality reflection line across the entire orogen, supplemented by the observed and inferred geological features to which reflections could be related, demonstrated that both the Superior and Hearne cratons were structurally isolated from the Reindeer zone and led to the discovery of a new microcontinent called the Sask craton (Lucas et al. 1993, 1994; Lewry et al. 1994; Ansdell et al. 1995).

The reflection data and their interpretation in different parts of the orogen provided a stimulus for further geological studies in specific areas. One example is a study of the composition, age and origin of rocks in the Rottenstone domain, a granite–migmatitic belt lying between a volcanic–plutonic island arc domain to the southeast (La Ronge domain) and the calc-alkaline Wathaman batholith to the northwest (Clarke et al. 2005). Another example is the detailed investigation of the basal detachment, the Pelican Thrust zone, between the Archean Sask craton and the Paleoproterozoic Flin Flon–Glennie complex in the central part of the THO (Ashton et al. 2005). The latter is the study that is summarily exemplified in the following paragraphs.

The Pelican Thrust zone is a 3 to 7 km-wide zone of Paleoproterozoic mylonite that encircles the Pelican tectonic window, a 500 km^2 area of Archean granitic (the Sahli granite), migmatitic and gneissic rocks, the largest of the four tectonic windows in the THO and the only one in the Flin Flon domain. The primary east-west reflection survey extended for more than 700 km across the orogen, from the Superior Province in the east to the Hearne Province in the west (e.g. White et al. 2005). Line 9 was recorded along a highway that ran east-west about 20 km south of the Sahli granite; Line 10 followed a road that ran north-south and crossed the tectonic window (Fig. 19). Figure 20 shows an interpreted reflection section for an eastern segment of Line 9 tied to Line 10 at their intersection (Pandit et al. 1998). Reflectivity is strong throughout most of the section but individual reflections are difficult to delineate. Line 10 crosses the exposed Pelican window, which is relatively non-reflective, so has a direct tie to the geology. Reflectivity tied to the Pelican Thrust zone dips north on Line 10 and east on Line 9, separating the underlying Archean Sask craton from the overlying Paleoproterozoic Kisseynew domain to the north (Line 10) and Flin Flon domain to the east (Line 9). Upper crustal reflectivity north and east of the Pelican Thrust zone is associated with geological features in the Kisseynew and Flin Flon domains, respectively.

The seismic images confirmed the role of the Pelican Thrust zone as a major detachment along which Paleoproterozoic allochthons were carried across the Archean Sask craton. However, understanding of the relationships was not strong, so further geological investigations were undertaken in the region of the Pelican Thrust zone to better elucidate the structural geology and tectonic development of the zone. Ashton et al. (2005) described this work. Early workers had misidentified mylonite in the Pelican Thrust zone because mylonitic textures were rarely preserved due to widespread dynamic crystallization. However, mylonitization was clearly indicated by large tectonic inclusions with medium grain size and pre-mylonitic texture that displayed sharp strain gradients into mylonite (e.g. Fig. 21a, b). The field studies enabled preparation of a detailed geological map of the area of the Pelican Thrust zone that showed structural relationships (figure 3 of

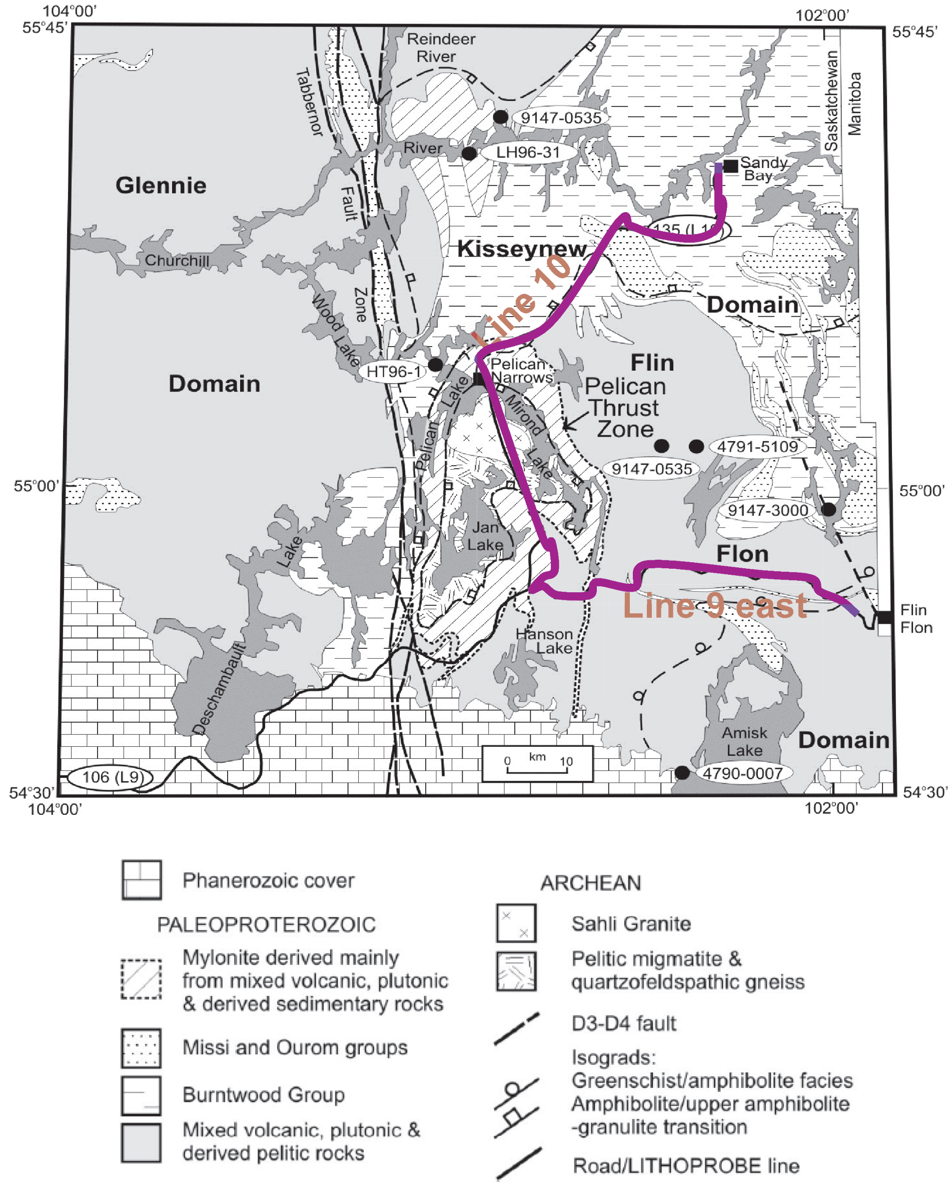

Figure 19. Simplified geological map of the Pelican window area (location 8 in Fig. 1) showing the Pelican Thrust zone (main area of Paleoproterozoic mylonite), locations of dated samples (dots), and the broad metamorphic gradient. Lithoprobe Line 9 east and Line 10 (see Fig. 20) are highlighted. Modified from Ashton et al. (2005).

Ashton et al. 2005). For example, kinematic indicators such as winged δ-porphyroclasts (Fig. 21c, d) indicate reverse to oblique dextral shear and southwest vergence, which is taken as the original sense of displacement on the Pelican Thrust zone (Ashton et al. 2005). Other work involved studies of the region surrounding the Pelican Thrust zone, including dating of various types of rocks (Fig. 22). For example, the metamorphic zircon age of a tonalite located some kilometres northwest of the Pelican Thrust zone (Fig. 22a), plus related information, confirmed the timing of upper amphibolite-facies metamorphism mantling the zone. Based on structural relationships between two shear zones, a mylonitized granite from the Spruce Rapids shear zone placed a maximum age of 1846 Ma for late-D2 deformation associated with the Pelican Thrust zone (Fig. 22c).

The new geochronological dates from Ashton et al. (2005), plus those from earlier work, and the detailed structural studies enabled Ash-

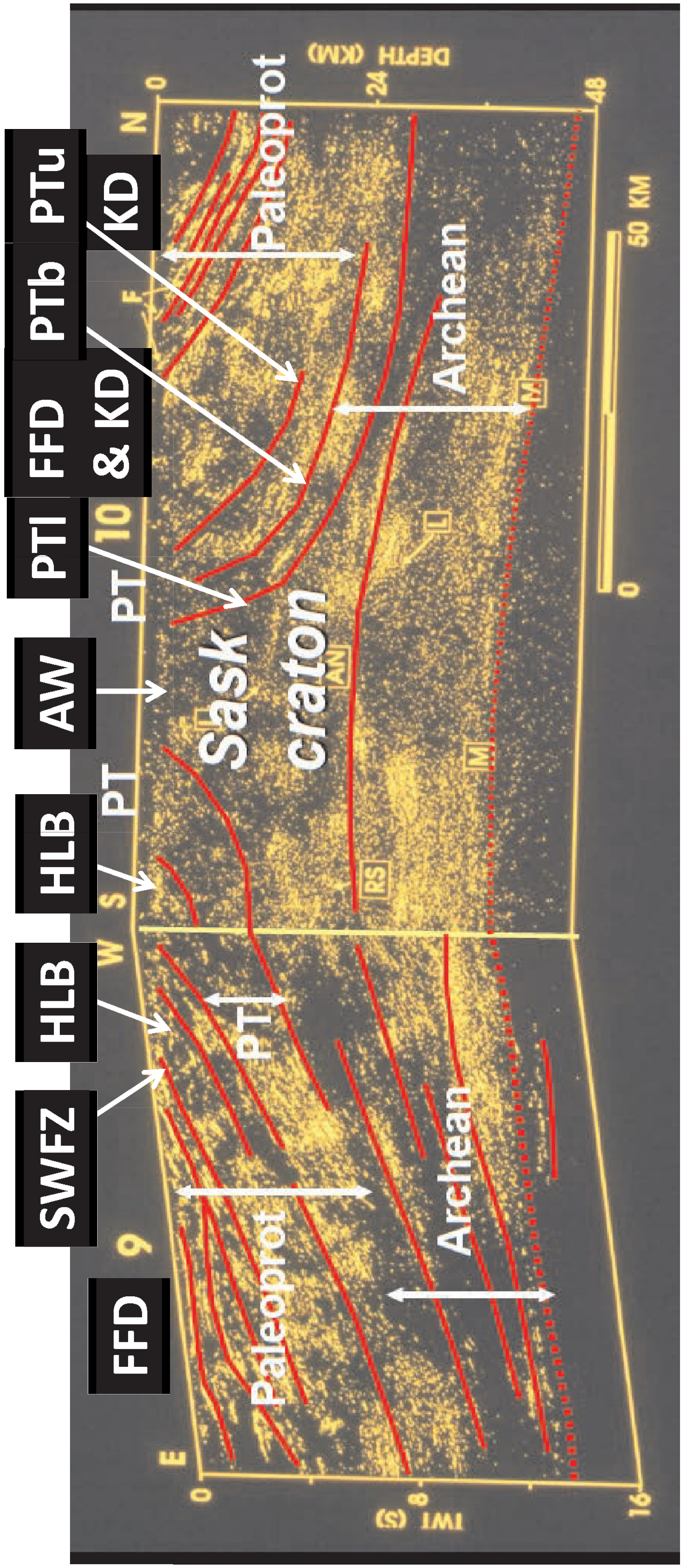

Figure 20. Interpreted seismic reflection section for Lithoprobe Line 9 east and Line 10 (location in Fig. 19). Abbreviations: AW, Archean window; F, faults; FFD, Flin Flon domain; HLB, Hanson Lake block; KD, Kisseynew domain; M, Moho; PT, Pelican Thrust zone; PTb, boundary between internal (Archean) and external (Paleoproterozoic) suites of Pelican Thrust zone (PT); PTl, lower boundary of PT; PTu, upper boundary of PT; SWFZ, Sturgeon-Weir fault zone. Yellow labels AN, L and RS identify specific reflection features not discussed in this paper.

ton et al. (2005) to develop a simplified model of tectonic evolution for the Pelican Thrust zone (Fig. 23). It shows abundant evidence of southwest-vergent thrusting, which began prior to 1826 Ma and possibly as early as 1845 Ma, and continued until at least 1806 Ma. Two later phases of regional deformation exposed the Pelican Thrust zone and underlying Archean window. Relative convergence between the Sask and Superior cratons below the overriding Flin Flon and Glennie domains during the period 1800–1770 Ma caused post-collisional shortening that was focused along the Tabbernor fault zone (Figs. 23, 19). Ashton et al. (2005) suggested that this may indicate reactivation of an early pre-existing tectonic discontinuity in the underlying Sask craton. Subsequent northeast-trending folds, which were likely caused by post-collisional shortening between the Hearne and Superior cratons, resulted in the domal structure that exposes the Pelican tectonic window.

GREENSTONE BELT IN THE WESTERN SUPERIOR PROVINCE

The western part of the Superior Province is the largest and best exposed Archean crustal block in the world and forms the nucleus of the North American continent (Fig. 1). The western Superior Province is characterized by a regional pattern of alternating, 100–200 km-wide granite-greenstone and metasedimentary belt-shaped subprovinces. The observed geologic relationships between and within these subprovinces are most often explained in terms of a modern tectonic model of terrane accretion (e.g. Hoffman 1989; Percival et al. 2006). Alternative scenarios are also proposed, although they typically refer to a different region of the Superior Province (e.g. Bédard et al. 2003). Lithoprobe studies in the Western Superior transect focused on testing the hypothesis that Archean continental lithosphere formed as a result of accretionary tectonics. To this end, three seismic reflection lines and two orthogonal (north-south, east-west) refraction profiles were recorded.

Reflection Line 1 was the main profile, extending from just north of Lake Superior to 'road's end',

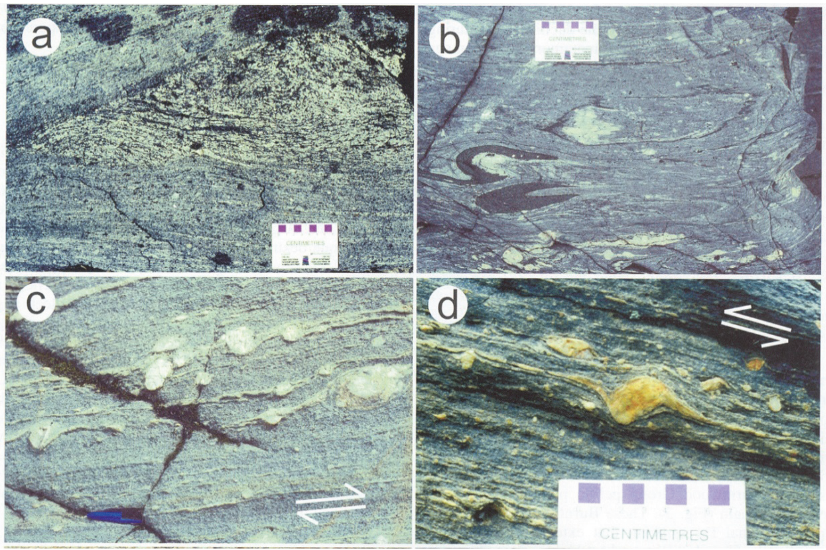

Figure 21. Structural geology examples from the Pelican Thrust zone (PTZ). *(a)* Strain gradient exhibited around tectonic inclusion of Paleoproterozoic gneissic granodiorite-tonalite in mylonite of the eastern PTZ. *(b)* Sheath fold defined by highly attenuated mafic dyke(s) in porphyroclastic mylonite, eastern shore of Mirond Lake (Fig. 19), eastern PTZ. *(c)* δ-winged porphyroclasts derived from coarse-grained to pegmatitic leucosome in mylonitic granodiorite-tonalite of the eastern PTZ indicating a dextral component of shear. *(d)* δ-winged porphyroclasts in mylonitized pelitic migmatite in eastern PTZ indicating low-angle reverse sense of shearing. From Ashton et al. (2005).

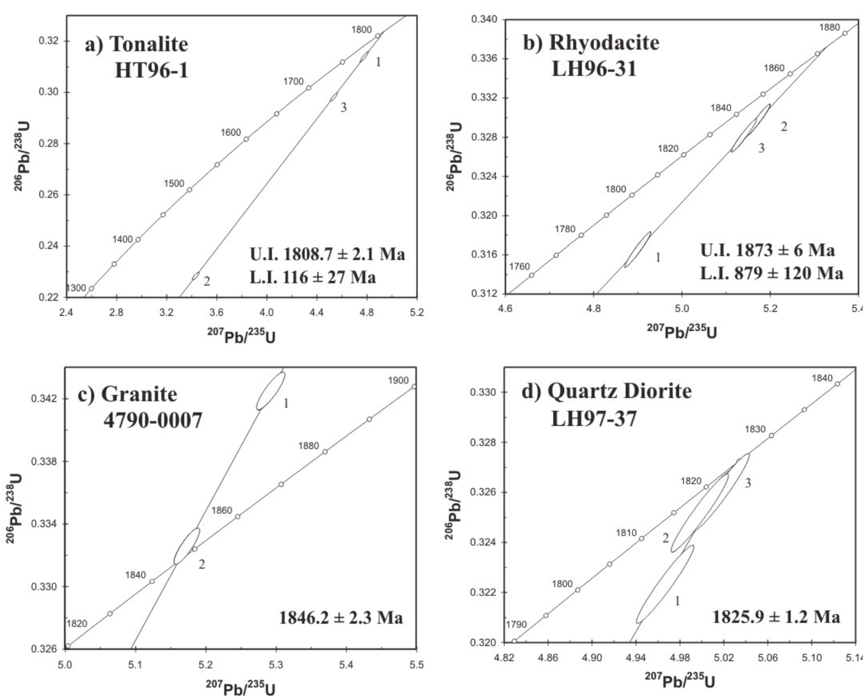

Figure 22. Exemplary Concordia diagrams for rocks in and around the Pelican Thrust zone (PTZ). *(a)* Post-Burntwood Group tonalite from the Kisseynew domain west of the Pelican window. *(b)* Gneissic rhyodacite from the Churchill River area. *(c)* Pre- to syn-tectonic granite from the Spruce Rapids shear zone on the western side of Amisk Lake. *(d)* Late-tectonic quartz-diorite dyke intruding mylonite in the re-emerged PTZ on the Churchill River. U.I., upper intercept; L.I., lower intercept; MSWD, mean square of weighted deviates. Site locations for (a), (b) and (c) are indicated in Figure 19. From Ashton et al. (2005).

almost 600 km north of the start point (see White et al. 2003). The north-south refraction line was recorded along the same road system as the main reflection line and the east-west profile bisected the former (see Musacchio et al. 2004). Reflection Line 3 was a short line (< 100 km long) recorded over a key geologic structure east of the main line. Reflection Line 2, also oriented north-south, about 230 km long and located about 250 km west of Line 1, is the focus of the following summary. It was recorded north to south from the Berens River plutonic complex, across the Red Lake greenstone belt, part of the Uchi volcanic-plutonic belt, across the English River metasedimentary belt and into the Winnipeg River tonalitic gneiss terrane (Fig. 24). Calvert et al. (2004) provided an interpretation of these data.

In a subsequent study, undertaken to complement the shallow (<1.5 km depth) reflection data for which tracing reflections to the surface is difficult, Zeng and Calvert (2006) derived near-surface *P*-wave velocity structure by analyzing the first (refraction) arrivals recorded during the reflection survey. Their main objectives were (1) to determine any correlations between *P*-wave velocity and lithological units or shear zones in and around the Red Lake greenstone belt, and (2) to correlate shallow seismic reflectors with variations in *P*-wave velocity as a means of helping to determine the geological origin of the reflectors. Their method of analysis involved a 3-D travel time inversion of a segment of Line 2 (stations 3000 to 8000, Fig. 24) because the total length of the line precluded inversion of the entire dataset for computational reasons, and the crooked geometry necessitated a 3-D approach.

Figure 25 shows the result of the analysis by Zeng and Calvert (2006), presented as a 2-D cross-section along the recorded profile. The maximum depth of well-constrained velocity values rarely exceeds 1 km, even with source-receiver offsets up to 12 km, due to the low velocity gradients typical of igneous and metamorphic rocks. The Red Lake greenstone belt at the north end of the profile segment is an Archean sequence of metavolcanic and metasedimentary

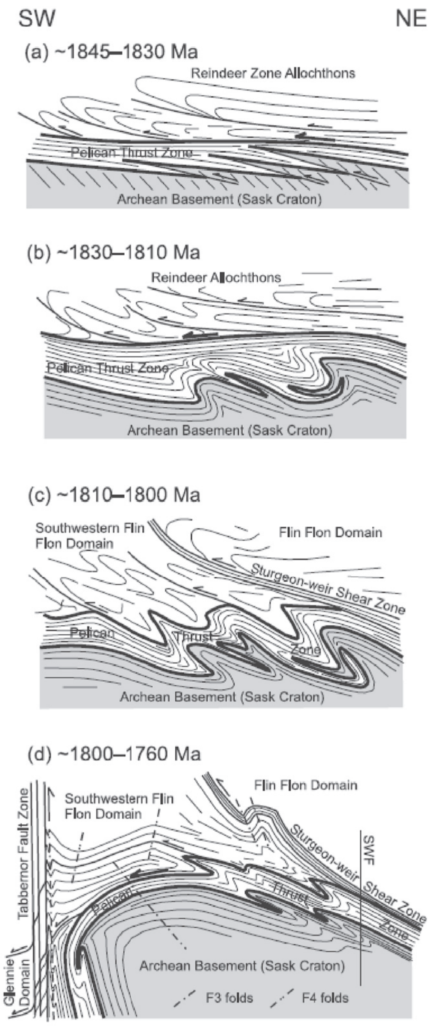

Figure 23. Schematic cross-sections illustrating development and subsequent deformation of the Pelican Thrust zone (PTZ); arrows indicate direction of tectonic transport; not to scale. *(a)* Pre-1830 Ma southward transport of Paleoproterozoic Reindeer zone allochthons across Archean Sask craton with possible imbrication (early D2 ± D1). *(b)* Thermal softening of upper Sask craton results in southwest-vergent D2 folding and continued thrusting. *(c)* Continued amplification of southwest-vergent D2 folds and initiation of Sturgeon-Weir shear zone as a rooted higher crustal-level splay of the folded PTZ (late D2). *(d)* Regional D3 north-south folding produces major west-vergent antiform and minor folding of Sturgeon-Weir shear zone. Coeval, reverse, east-side-up displacement along Tabbernor fault zone creates zone of intense strain between it and competent Sask craton. Circa 1770 Ma post-collisional D4 shortening produces regional northeast-trending upright folds and sinistral displacement along brittle Tabbernor and Sturgeon-Weir (SWZ) faults. From Ashton et al. (2005).

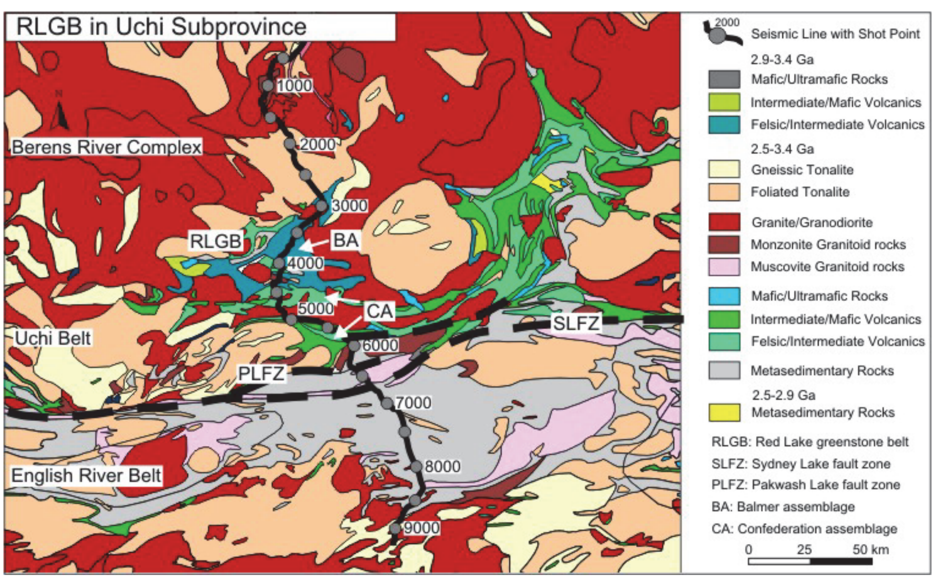

Figure 24. Geological map of the Red Lake greenstone belt (RLGB) in the Uchi volcanic-plutonic sub-province (location 9 on Fig. 1) and location of seismic reflection profile. Major assemblages and three faults (dashed black lines) immediately north of the English River metasedimentary belt are from Sanborn-Barrie et al. (2004). From Zeng and Calvert (2006).

rocks, subdivided into several assemblages with varying ages, and is an active gold-mining region. Its two main assemblages are the Mesoarchean Balmer (3000 Ma to 2960 Ma, Corfu and Andrews 1987) and the Neoarchean Confederation (2750 to 2730 Ma, Stott and Corfu 1991; Fig. 24). The Balmer assemblage forms about 50% of the belt and consists mainly of interlayered basaltic and komatiitic flows and mafic to ultramafic intrusive rocks (Sanborn-Barrie et al. 2000). Based on the extent of mafic to ultramafic mineralogy in these rocks (e.g. Fig. 26), they are expected to have relatively high seismic velocities (e.g. Christensen and Mooney 1995; Ji et al. 2002). The Confederation assemblage consists of intercalated felsic to mafic metavolcanic flows, pyroclastic rocks and metasedimentary rocks of volcanic provenance (Sanborn-Barrie et al. 2000). Given that these rocks include a higher component of felsic material than the Balmer assemblage (e.g. Fig. 27), they are expected to have a significantly lower seismic velocity (e.g. Christensen and Mooney 1995; Ji et al. 2002).

In Figure 25, high *P*-wave velocities (up to 7.0 km/s) in the Balmer assemblage (approximately stations 3250 to 4080) are consistent with values expected from mineralogy and thus indicate a significant component of ultramafic rocks in this region. Its northern boundary is defined by an abrupt decrease in velocities to about 5.8 km/s. Its southern boundary, where the velocities do not exceed 6.4 km/s, is associated with a well-defined 5.5 km-wide, 800 m deep, low-velocity anomaly that correlates with an unconformity with the Confederation assemblage. Within the latter, which extends from about station 4080 to 6000, velocities generally do not exceed 5.8 km/s, although there are a few localities below 500 m depth where velocities exceed 6.0 km/s. These values are consistent with the Confederation assemblage having a less mafic content than the Balmer assemblage. Velocities to depths of about 1000 m in the English River metasedimentary belt (south of station 6080) are noticeably lower than in the Red Lake greenstone belt. In particular, low velocities (5.1–5.4 km/s) and low velocity gradients

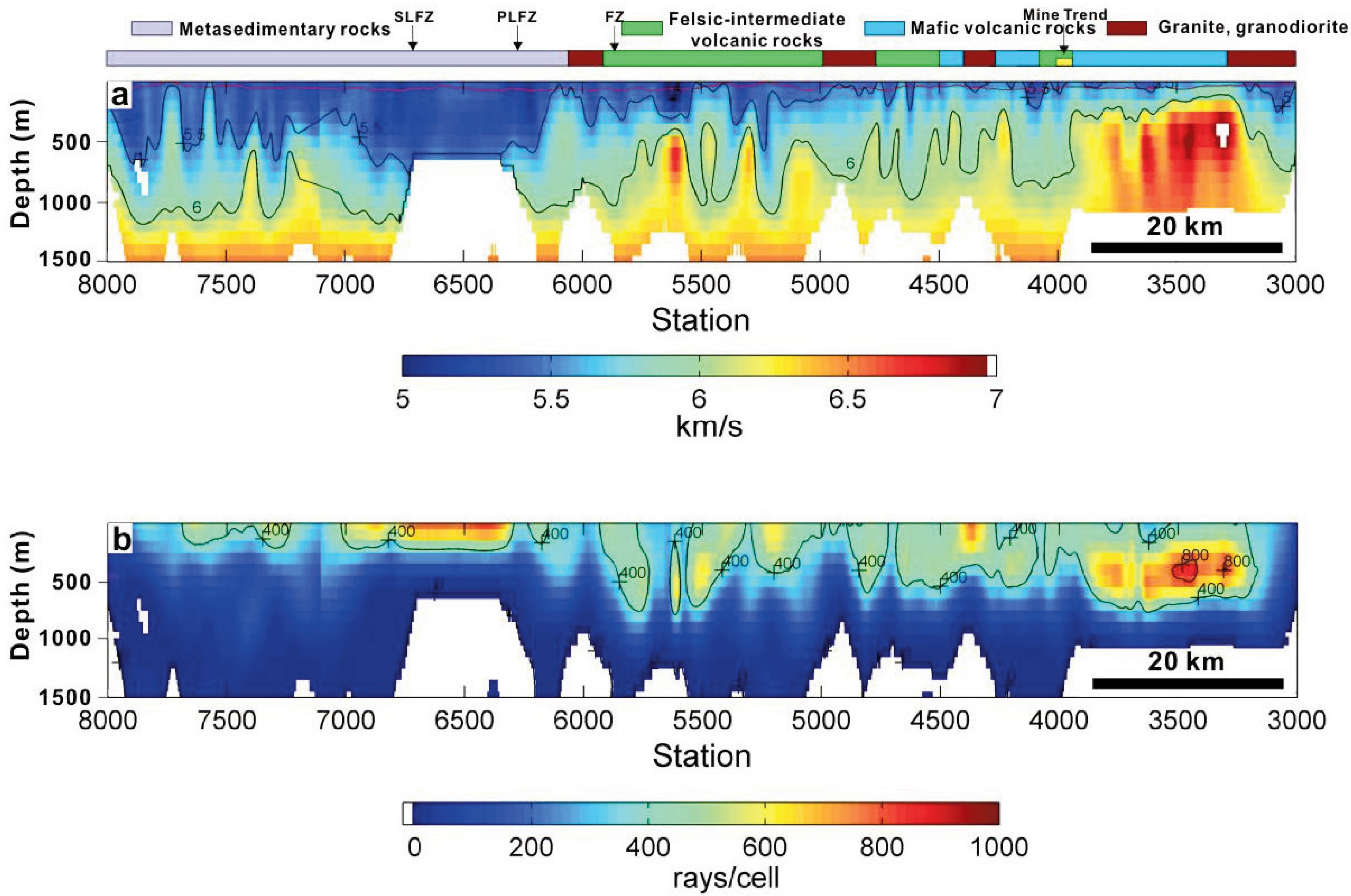

Figure 25. *(a)* Vertical section through the final 3-D velocity model corresponding to the profile along which the seismic data were acquired (Fig. 24). Ground level is indicated by the thin red line. Isocontours at 5.5 km/s and 6.0 km/s are shown by the thin black lines. Geology along the profile is indicated above. Abbreviations: FZ, unnamed fault zone; PLFZ, Pakwash Lake fault zone; SLFZ, Sydney Lake fault zone. *(b)* Vertical section showing the density of rays in each 100 m x 100 m x 100 m cell of the model displayed in (a); the higher the density of rays, the better resolved are the velocities. Depths are relative to a datum of 450 m above mean sea level. Vertical exaggeration is 12.5:1. From Zeng and Calvert (2006).

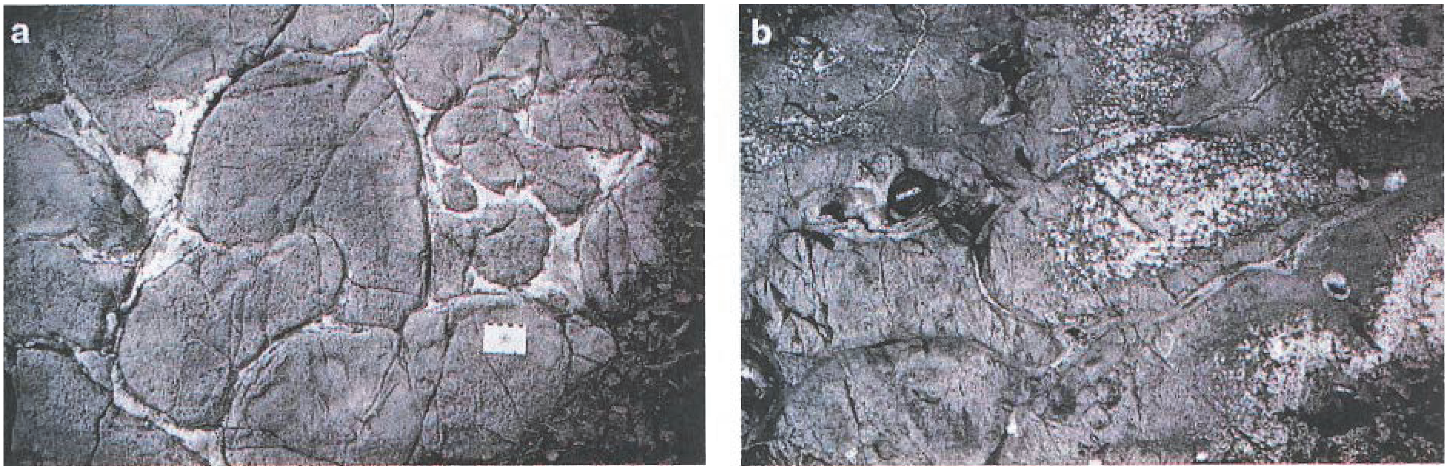

Figure 26. *(a)* Pillowed komatiitic flow with interpillow chert from Mesoarchean Balmer assemblage in the Red Lake greenstone belt; centimetre scale shown. *(b)* Pillowed basalt from Balmer assemblage; lens cap shows scale. These rocks generally have higher seismic velocities than those from the Neoarchean Confederation assemblage (Fig. 27). From Sanborn-Barrie et al. (2000).

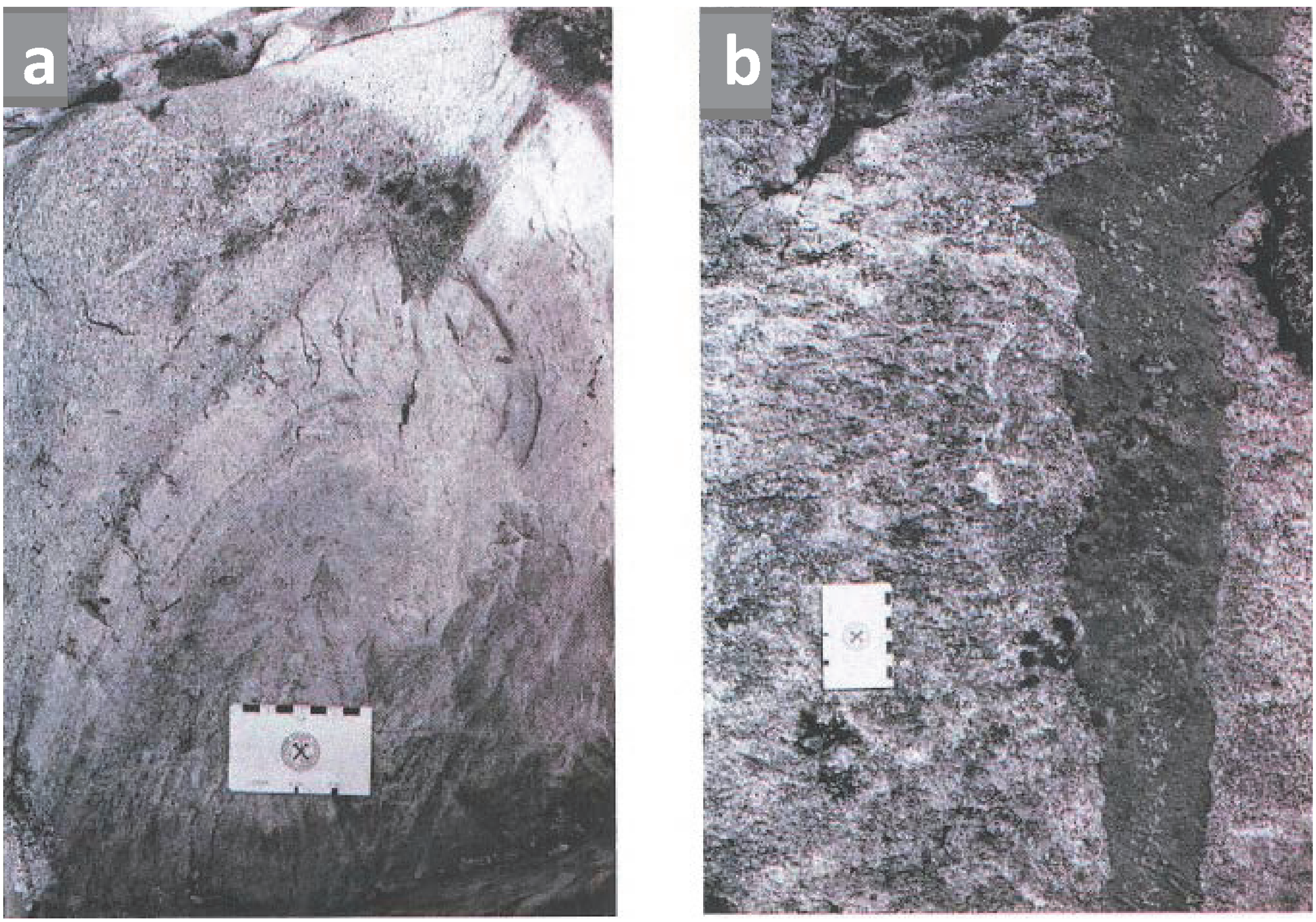

Figure 27. *(a)* Rhyolite lobe from Neoarchean Confederation assemblage in the Red Lake greenstone belt. *(b)* Rhyolite tuff from Neoarchean Confederation assemblage; the tuff breccia is cut by a plagioclase-phyric andesite dyke. Centimetre scales are shown. From Sanborn-Barrie et al. (2000).

between stations 6200 and 6800 are associated with the Sydney Lake fault zone, a strike-slip fault zone that can be traced discontinuously along the Uchi–English River boundary for 440 km, and its splay, the Pakwash Lake fault zone, which merges with the Sydney Lake fault zone to the west. Fracturing or mylonitization of the rocks within the fault zone may provide one explanation for these low velocities. The low velocities and velocity gradients extend for about 13 km along the seismic line, consistent with surface geological mapping of multiple faults. However, because the seismic line runs approximately perpendicular to the strike of the fault zones, the low seismic velocities also imply that rocks within a few kilometres of the two fault splays have undergone deformation that has reduced their seismic velocity (Zeng and Calvert 2006).

Figure 28 shows these features from the 3-D velocity model superimposed on a migrated seismic reflection section to 15 km depth and its interpretation. Reflectivity is strong below the Red Lake greenstone belt but generally chaotic below the English River metasedimentary belt. The interpretation indicates a possible fault associated with the unconformity between the Balmer and Confederation assemblages and hypothesizes another fault near the boundary between the Confederation assemblage and the metasedimentary rocks. The Sydney Lake and Pakwash Lake fault zones are poorly imaged on the reflection section but are well-defined near the surface by their low velocities and velocity gradient on the velocity section. Figures 25 and 28 demonstrate the complementary information provided by detailed velocity analyses of the uppermost crust, in which rock types and faults can be related to surface geology, and the migrated reflection section, from which little information can be inferred for the upper 2 km.

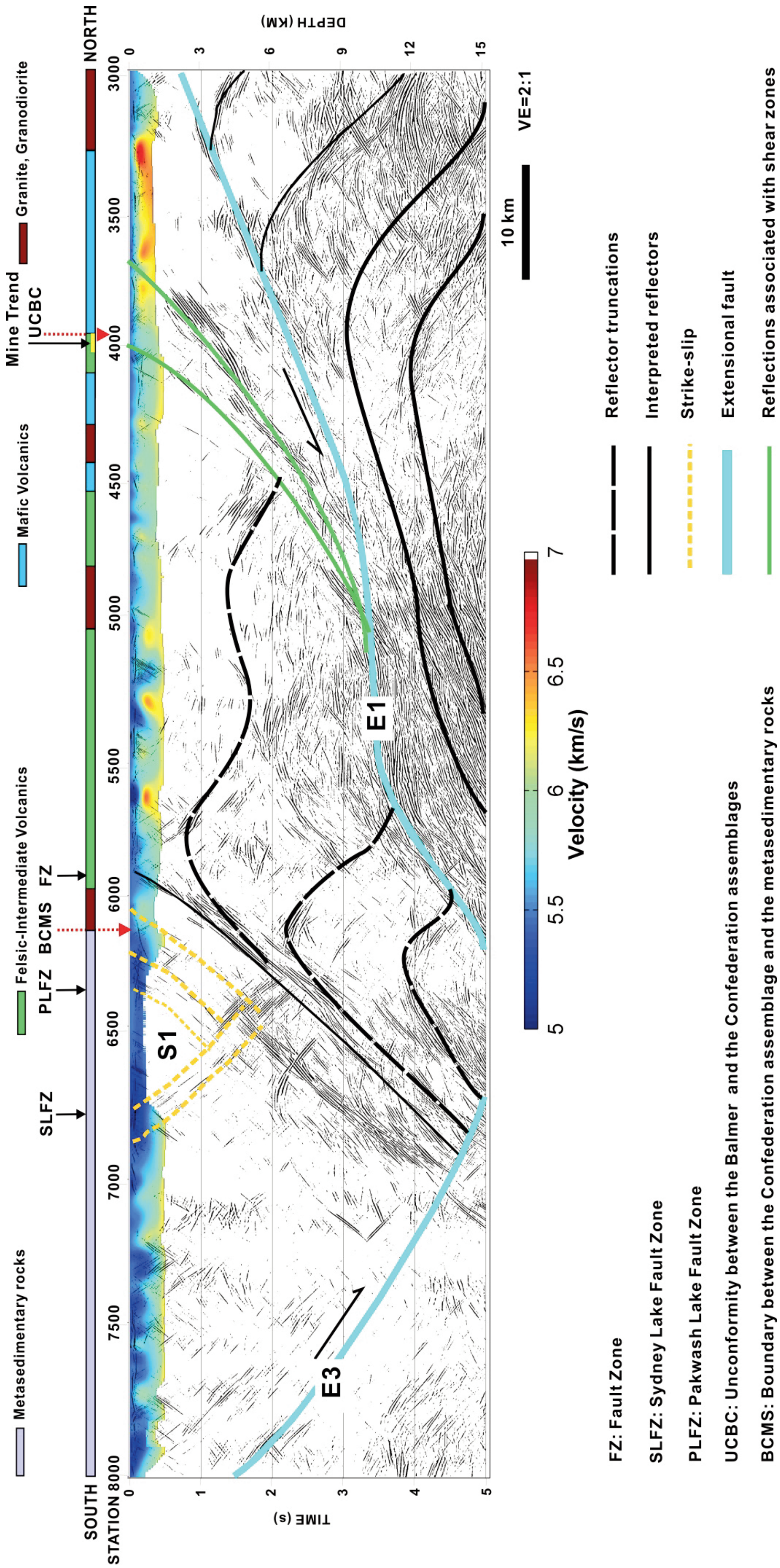

Figure 28. Interpretation of migrated reflection section to 15 km depth on which is overlain a vertical section extracted from the 3-D velocity model along the line of common-depth-point bins. Blue lines indicate extensional shear zones (E1, E3) that penetrate to the mid-crust. Yellow lines indicate faults associated with the Sydney Lake fault zone (S1). Green lines indicate hypothesized shear zones associated with the Balmer assemblage. Black lines indicate the orientation of reflection fabrics within the crust. Lines are shown dashed where less certain. From Zeng and Calvert (2006).

CONCLUSIONS

The preceding eleven examples demonstrate the quality and detail of interpretations that can be achieved through the collaborative efforts by geophysicists and geologists. The dominant message to be taken from this contribution is that further progress in the Earth sciences will be achieved primarily by such collaborative efforts. This message has an associated corollary that also is illustrated by these examples: multidisciplinary studies, which inevitably are considered when collaboration is a key, also are fundamental to further progress in our science. In this article, I have presented examples of only some of the many Lithoprobe studies that underline this message. Within many of Lithoprobe's 1500+ publications, these messages are demonstrated over and over again. My hope, and expectation, is that these and similar messages from other studies will encourage all Earth scientists to recognize and benefit from the advantages of collaborative, multidisciplinary research.

ACKNOWLEDGEMENTS

Results presented in this article derive from publications of many Lithoprobe scientists who are cited in the reference list. I thank them for their contributions to this work and to the project as a whole. In particular, I thank Carol Evenchick of the Geological Survey of Canada, Vancouver and Andrew Calvert, Simon Fraser University for providing me with illustrations deriving from their research. I also thank the hundreds of other Lithoprobe scientists for their contributions to the project over its 22-year history. Our work helped shape the nature of Earth science research in Canada and beyond. This article was improved substantially as a result of reviews by Sandra Barr, Andrew Hynes and an anonymous reviewer.

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Received April 2014
Accepted as revised September 2014
First published on the web December 2014