How the crust meets the mantle: Lithoprobe perspectives on the Mohorovičić discontinuity and crust–mantle transition[1]

Frederick A. Cook, Donald J. White, Alan G. Jones, David W.S. Eaton, Jeremy Hall, and Ronald M. Clowes

Abstract: Application of regional geophysical and geological methods throughout two decades of Canada's Lithoprobe project provides new opportunities to analyze the Mohorovičić discontinuity (Moho) and crust–mantle transition. The transect format employed during Lithoprobe, in which 10 specified regions of Canada were targeted for approximately a decade each, between 1984 and 2003, permitted teams of scientists to focus on geological, geophysical, and tectonic issues for each transect. As a primary objective was to enhance knowledge of the structure of the crust and lithosphere, an obvious target in each transect was the nature and origin of the Moho and crust–mantle transition. Accordingly, the combined results provide new perspectives on the Moho and the relationship of the Moho to the crust–mantle transition. Perhaps the most important result is that the continental geophysical Moho is a deceptively simple feature; it has a variety of signatures at different scales that preclude a single, universally applicable interpretation. In methods that provide large-scale information, such as regional seismic studies, it is a relatively abrupt refraction velocity contrast that often displays a dramatic downward decrease in seismic reflectivity. However, its origin in a geological or tectonic sense is perhaps best determined by careful analyses of structural details near the geophysical Moho, which are complex and varied. In some areas within Canada, it appears that the geophysical Moho may be old and perhaps remains from the time the crust formed; in other areas, it appears to be a relatively young feature that was superimposed onto older crustal fabrics.

Résumé : L'application de méthodes géophysiques et géologiques régionales durant les deux décennies du projet canadien Lithoprobe a fourni de nouvelles possibilités d'analyser la discontinuité de Mohorovičić (Moho) et la transition croûte–manteau. Le format de transects utilisés durant Lithoprobe, selon lequel 10 régions spécifiques du Canada ont été ciblées pour environ une décennie chacune entre 1984 et 2003, a permis à des équipes de scientistes de se pencher sur les enjeux géologiques, géophysiques et tectoniques de chaque transect. Puisqu'un des principaux objectifs était de rehausser la connaissance de la structure de la croûte et de la lithosphère, une cible évidente dans chaque transect était la nature et l'origine de la transition entre le Moho et la croûte–manteau. Les résultats combinés fournissent donc de nouvelles perspectives du Moho et de la relation du Moho à la transition croûte–manteau. Le résultat peut-être le plus significatif est que le Moho géophysique continental est une caractéristique dont la simplicité est trompeuse; il possède plusieurs signatures à différentes échelles qui empêchent une interprétation unique et universellement applicable. Lorsque les méthodes donnaient de l'information à grande échelle, par exemple les études sismiques régionales, il se présente comme un contraste de vitesse de réfraction relativement abrupt, souvent avec une diminution de réflectivité sismique vers le bas. Toutefois, son origine dans un sens géologique ou tectonique est peut-être le mieux déterminé par une analyse soignée des détails structuraux à proximité du Moho géophysique, et ces détails sont complexes et variés. Dans certains secteurs du Canada, il semble que le Moho géophysique puisse être vieux et constituer un vestige du temps de formation de la croûte; dans d'autres secteurs, il semble constituer une caractéristique jeune qui a été superposée sur des fabriques plus anciennes de la croûte.

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F.A. Cook[2] and D.W.S. Eaton. Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4, Canada.
D.J. White. Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada.
A.G. Jones. Dublin Institute for Advanced Studies, Geophysics Section, 5 Merrion Square, Dublin 2, Ireland.
J. Hall. Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL A1B 3X5, Canada.
R.M. Clowes. Department of Earth and Ocean Sciences, The University of British Columbia, 6339 Stores Road, Vancouver, BC V6T 1Z4, Canada.

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[2]Corresponding author (e-mail: fcook@ucalgary.ca).

Introduction

General

The most important globally correlatable boundary within the Earth's lithosphere is the transition from the crust to the mantle; knowledge about its structure, physical properties, and origin are crucial to understanding the formation, deformation, and destruction of lithosphere. Accordingly, one of the great opportunities provided by the multitude of Lithoprobe data across Canada has been the delineation of various characteristics in the vicinity of the continental crust–mantle transition. The magnitude of the Lithoprobe datasets is unique, both in lengths of geophysical profiles and in variety of regions studies, coupled with the consistent focus on obtaining high-quality regional deep information. The acquisition of varieties of data, including controlled-source seismic (refraction and reflection), natural-source seismic, potential-field, electromagnetic, and regional geology data, that are concentrated within specific regions and focused on key lithotectonic problems has been the hallmark of the project. The purpose of this contribution is to review some of the findings related to the crust–mantle transition and synthesize these results into a perspective that has global implications.

The crust–mantle transition is important historically because it is the first globally identified subsurface boundary; it is the most accessible, global boundary (other than the Earth's surface); and it is shallow enough to be studied using a number of geophysical and geological techniques. Indeed, fragments of the oceanic crust–mantle transition appear to be exposed, though rarely, in exhumed rocks such as ophiolites; and there are some locations where it has been suggested that the continental crust–mantle boundary is exposed. The transition is important petrologically because it represents the change from silica-rich rocks above to primarily ultramafic rocks below. Although it is clear that this lithologic distinction has developed as a result of global differentiation over geologic time, it is not well known why it forms as a relatively rapid vertical change and the subsequent interaction of crustal rocks above with mantle rocks below. Many of the Lithoprobe data provide valuable information on these characteristics.

Historically, the crust–mantle transition and the Moho have been used as interchangeable terms. However, as various datasets, both geophysical and geological, have provided increasing detail of petrological and geometric changes in the vicinity of the transition, it has become clear that the Moho (a geophysical representation) and the crust–mantle transition (the geological change) may not always represent the same boundary.

In Lithoprobe, the traditional seismic refraction Moho is a ubiquitous feature in all of the transects, although the resolution of velocity structure and the often collocated seismic reflection and electromagnetic profiles permit correlations on regional scales that are rarely possible elsewhere in the world. In Lithoprobe reflection profiles, detailed resolution of structures in the vicinity of the crust–mantle transition has led to new interpretations of the interactions between lower crustal structures and the upper mantle. In Lithoprobe electromagnetic profiles, the first evidence of an "electric Moho" in the Slave Province was found. Accordingly, the purpose of this paper is to synthesize these results into a coherent understanding and a generic model for the origin and tectonic significance of the continental Moho and crust–mantle transition. To appreciate and understand some of the implications of these results, we begin by reviewing the developmental history of this important transition.

The Moho

Andrija Mohorovičić (1910*a*, 1910*b*) first described a subsurface discontinuity (later called the Mohorovičić discontinuity or "Moho") on the basis of an interpretation of regional earthquake recordings in Europe. Mohorovičić recognized that a change in slope of seismic first arrivals at increasing distance from a seismic source could be interpreted as the response to a rapid change in seismic compressional wave velocity from $\sim$5.60 to >7.75 km/s near 50–54 km depth and seismic shear waves from 3.27 to 4.18 km/s in that area. Because the discontinuity was defined on the basis of seismic head waves (waves that are refracted along, or slightly beneath, a discontinuity), the Moho sensu stricto is the velocity change. Subsequently, controlled-source refraction surveys, which also measure the propagation of head waves, but with greater detail than for earthquake studies, have been used to map the Moho around the world and thus delineate the transition from the crust above to the mantle below.

The substantial, and vertically abrupt, change in wave velocity has been interpreted in a number of ways, some of which will be discussed later in the paper. However, a common thread in all interpretations is that the higher velocities below the discontinuity are associated with rocks that are denser and less compressible than those above the discontinuity (e.g., Adams and Williamson 1923). A large contrast in depth to the Moho is found between continents and oceans, where the depth is typically between 30 and 70 km and $\sim$10 km, respectively. However, there is substantial variation in both the magnitude of the velocity contrast and the vertical dimension of the transition, particularly within continental regions where an array of geological processes has influenced the nature of the Moho over long periods of geological time. In an effort to provide a globally consistent definition, Steinhart (1967) proposed that the refraction Moho be the depth at which the *P*-wave velocity first increases rapidly or discontinuously to 7.6–8.6 km/s. If steep velocity gradients are not present, then the refraction Moho is interpreted as the level at which the *P*-wave velocity exceeds 7.6 km/s (Steinhart 1967; Jarchow and Thompson 1989). This has been adopted as the definition by the geophysical community and ensures that a refraction Moho will be found everywhere around the world.

In addition to mapping the location of the Moho, an important opportunity provided by the Lithoprobe datasets is to analyze the detailed structures and properties of rocks in the vicinity of the Moho throughout much of Canada. Therefore, a primary theme of this synthesis, in addition to reviewing the position of the Moho from refraction profiles, is to present results from the datasets that allow detailed structures and physical properties of rocks near the Moho to be mapped. To accomplish this, it is necessary to review the definitions of the Moho as described on other types of remotely sensed data.

The reflection Moho

As controlled-source seismic data were acquired at increasingly narrow incident angles in the 1960s and 1970s, reflection responses from the vicinity of the refraction Moho were found to be variable. In some regions, there are no reflections visible; in others, reflections are prominent single events; and in still others, complex geometric features are observed. The complexity of reflection characteristics in the vicinity of the Moho has led to a variety of new interpretations for this seismic boundary and thus for the crust–mantle transition (e.g., Hynes and Snyder 1995; Hammer and Clowes 1997; Cook 2002).

Regardless of how the details of reflection geometry are interpreted, the most dominant characteristic of virtually all good reflection profiles is that the crust is considerably more reflective than the mantle (e.g., Hammer and Clowes 1997; Cook 2002). For this reason, the "reflection Moho" has been defined as the deepest, high-amplitude, laterally extensive reflection or group of reflections present at travel times (depths) approximately commensurate with other estimates of crustal thickness (e.g., Klemperer et al. 1986). This may be due, in part, to different wavelength scales of mantle returns (longer wavelengths; Wu and Flatte 1990; Tittgemeyer et al. 1999) compared with crustal reflections; but it appears to occur regardless of the geometry of the crustal reflections near the transition.

Lithoprobe has acquired >12 000 km of high-quality reflection profiles that address the nature of reflections in the vicinity of the crust–mantle transition (Cook 2002). These datasets are unusually valuable because, individually, they are some of the highest quality (in terms of reflection continuity and correlatability) and because, collectively, they provide some of the most easily comparable data, due to the generally similar, albeit evolving, acquisition, and processing methods used throughout most of the Lithoprobe program.

The electric Moho

The "electric Moho" is defined as a step change in electrical conductivity, which occurs at a depth that is in the vicinity of the depth of the refraction Moho (Jones and Ferguson 2001). The pioneering and serendipitous discovery during Lithoprobe revealed a rapid change in electrical conductivity at depths that correlate with the refraction Moho. High-quality magnetotelluric data from sites west of Yellowknife in the Slave Craton were analyzed and modelled to exhibit a reduction of over an order of magnitude in electrical conductivity, from resistivities of 40 000 to 4000 Ω·m at a depth of 35.8 ± 1.5 km (Jones and Ferguson 2001). This resolution of an "electrical Moho" was made possible because of the lack of conducting material in the crustal column. Typically, any conductivity variation at the Moho is masked by the effects of a conducting lower crust (Jones 1992). However, the southern part of the Slave Craton is unusual — or so was thought at the time — of exhibiting very low crustal conductivity, <1 S as compared with more typical values of 20–40 S for Archean regions and 100 to >1000 S for younger to active regions.

Since Jones and Ferguson's (2001) discovery, other areas have been found that exhibit low crustal conductivity, thereby facilitating identification of an electric Moho. These include the Eastern India Craton (Bhattacharya and Shalivahan 2002), the Rae Craton in Canada (Jones et al. 2002; Evans et al. 2005), and the Wopmay Orogen of Canada (Spratt et al. 2008). Another area that exhibits low crustal conductivity is the western part of the Cordillera along Corridor 3 of the Slave – Northern Cordillera Lithosphere Evolution (SNORCLE) project transect (Ledo et al. 2004). In this area, there is an increase in conductivity just below the seismic reflection-defined Moho (Ledo et al. 2004).

Laboratory studies suggest that a decrease in conductivity, or increase in resistivity, would be more likely when going from dominantly mafic lower crustal rocks to ultramafic upper mantle rocks. In some studies, this is observed, although the definition of the base of a more conductive region is difficult in electromagnetic studies. In other studies, including the original observation by Jones and Ferguson (2001), the mantle is more conductive, or less resistive, than the lower crust. This is difficult to explain, as common explanations for enhanced conductivity are not without major objection. Spratt et al. (2008) speculated that their observation beneath the boundary between the Slave Craton and the Bear Province can be explained by appealing to the laboratory observation of Ten Grotenhuis et al. (2004), in which conductivity is inversely related to grain size. This phenomenon can be understood as a surface boundary effect — the smaller grains have greater surface area, thus they facilitate surface conduction. Unfortunately, given the existence of the conducting lower crust on almost all other Lithoprobe transects, electromagnetic data could not contribute further to the discussion of the nature of the Moho.

Other constraints on the Moho

Potential-field data have been used in Lithoprobe studies to provide ancillary information on variations in mass (gravity) or magnetic response of the crust. However, neither of these methods produces direct images of the Moho or crust–mantle transition. Nevertheless, in combination with other observations, principally seismic ones, potential field observations are helpful for constraining interpretations of lower crustal and upper mantle structures and properties.

Magnetic data rarely respond to rocks as deep as the Moho because variations in magnetic anomalies depend on differences in magnetic susceptibilities and (or) remanent magnetization of rocks, which in turn depend on temperature. For temperatures in excess of the Curie temperature (typically ∼500–550 °C), these magnetic properties vanish. Thus, when these temperatures are exceeded at depths that are shallower than the Moho, properties of rocks near the Moho are usually beyond detection.

Gravity measurements are responsive to mass variations throughout the Earth; however, two key properties limit the usefulness of gravity for mapping variations near the Moho. First, the resolution of the method decreases substantially as the distance between the source and the measuring instrument increases. For the measurements made on the Earth's surface, only large-scale variations in Moho depth are easily detected. Second, in interpretation of gravity data without additional information (e.g., seismic profiling), there is an inherent ambiguity between structure and mass variation.

For example, broad, near-surface density variations can produce similar gravitational responses to local density variations at depth. However, when additional information is available, gravity anomalies can provide useful information for mapping Moho depth variations and density variations near the Moho (e.g., Martinec 1994).

The "geophysical Moho"

For the purpose of this paper, it is helpful to synthesize these geophysical observations into a definition of a boundary that is most easily referred to as the "geophysical Moho." In all cases when different geophysical techniques have been used to map variations in the corresponding property (e.g., structure, reflectivity, density, and conductivity) interpreted near the Moho, the appropriate modifier such as "reflection Moho," "electric Moho," etc. has been employed to the changes at appropriate depths for the Moho. The term "geophysical Moho" is thus applied here to refer to the boundary detected by remote-sensing geophysical techniques that is at or near the boundary detected by the original Moho detection method, refracted seismic head waves. This terminology is helpful to distinguish the transition observed using geophysical techniques and the petrologically defined crust–mantle transition, which may not necessarily correspond to variations in geophysical properties.

Significance of the Moho and crust–mantle transition

Historical setting

The discovery by Mohorovičić (1910*a*, 1910*b*) of a transition in seismic-wave velocity beneath Europe was the first documented evidence of what was to become the globally correlative boundary that defines the boundary between two of the concentric "shells" near the surface of the Earth, the crust and the mantle. Prior to the discovery of the Moho, globally concentric geometry had been speculated upon (e.g., Kircher 1665) and the core had been identified (Oldham 1906), but no observational evidence had been obtained for the outer layers. Ever since Mohorovičić's work, however, the nature and significance of the Moho and crust–mantle transition have been debated. Perhaps the most vehement discussions about the Moho and crust–mantle transition took place in the 1960s when two disparate and apparently (at the time) inconsistent views were presented (Ito and Kennedy 1971; Green and Ringwood 1972).

Correlation of petrologic interpretations to the refraction Moho

The technological advances in experimental petrology that took place in the years prior to the 1960s provided an opportunity for correlating petrologic changes to the seismic-refraction responses that had by then been found in most areas of the world. Essentially, the petrologic interpretations of the Moho evolved into two categories: (1) a compositional change from mafic rocks (e.g., mafic granulites and gabbros) above the transition to peridotitic rocks below (e.g., Green and Ringwood 1972) and (2) a phase (metamorphic) change from mafic granulites above the transition to eclogitic rocks below (Robertson et al. 1957; Kennedy 1959; Ito and Kennedy 1971).

In most of the discussions that took place at that time, there were two implicit assumptions. First, the Moho – crust–mantle transition was assumed to be the same everywhere on the continents and, in particular, to be associated with the transition from rocks with basaltic composition above to those with ultramafic composition below. Second, the crust–mantle transition was assumed to correlate, both spatially and geologically, with the geophysical boundary. However, as additional and higher resolution data have become available, it appears that these assumptions are not applicable as a general rule. Enhanced resolution of modern data over results that were used to define the regional significance of the seismic boundary has demonstrated geometric, and thus structural and petrologic, complexities in the vicinity of the Moho. In some regions, this complexity allows interpretations in which the geophysical Moho may be a response to mineralogical changes that are part of a geological continuum and overlie a deeper transition, the true crust–mantle transition, between ultramafic rocks that have different origins. As a result, it is necessary to have detailed resolution of structures and lithology in the vicinity of the Moho and crust–mantle transition. Most geophysical tools simply do not provide sufficient detail.

The earliest suggestion that the upper mantle is composed of eclogite and that eclogite is a high-pressure form of basalt was made by Fermor (1914). Holmes (1931) recognized that the seismic velocity of eclogite is similar to velocities that had by then been observed for the layer below the Moho (Mohorovičić 1910*a*, 1910*b*) and proposed that the Mohorovičić discontinuity represents a transformation from gabbroic rocks to eclogite.

One of the major arguments in opposition to a phase change at the Moho derived from the observation that the velocity transition mapped on refraction profiles occurs over a relatively short vertical distance (Green and Ringwood 1972), in contrast to a broader transition (pressure and depth) interval observed in laboratory experiments on the mafic granulite-to-eclogite phase transition for rocks of basaltic composition (Green and Ringwood 1972). Accordingly, Green and Ringwood (1972) suggested that the seismic-refraction results were inconsistent with the transition as a gradual phase change.

As resolution in seismic methods, both refraction and reflection, has improved, substantial variability in the nature of the seismic changes near the crust–mantle transition has been observed. In some areas, the transition appears to be relatively abrupt, whereas in others it appears to be more gradual. In some areas, there are complex structures associated with it; in other areas, the structures are relatively simple. This is important because, at the scales of resolution now available (kilometres to hundreds of metres), the Moho and crust–mantle transition clearly have substantial variability in seismic properties. Thus, the assumption that the Moho is the same everywhere appears to be incorrect.

The second assumption that the geological transition from crust to mantle coincides with the geophysical change (Moho) is to some extent dependent on the definition of the "crust–mantle" transition. As increasing quantities and resolution of data have become available, the possibility that large tracts of rocks below the geophysical Moho may have been part of the lower crust that underwent partial melting and extraction of the light fractions (e.g., Wyllie 1971) has been revived and proposed as a possible mechanism for the formation of the Moho in some regions (e.g., Hynes and Snyder 1995; Cook 2002). Even Ito and Kennedy (1971) recognized that the continental Moho may not always represent the same boundary, as they proposed that in some areas it may coincide with a compositional change (e.g., gabbroic rocks to peridotitic rocks), whereas in others it may be a phase change (e.g., from basaltic rocks to garnet granulite or from garnet granulite to eclogite).

These interpretations are significant for understanding how the interactions between the crust and upper mantle phase changes, such as mafic granulite to eclogite, are responsible for the geophysical transition. For example, because a phase change may occur where temperature and (or) pressure variations are transient, they may metamorphose rocks in the lower crust to rocks with geophysical properties that are appropriate for the mantle. Such alterations are generally irreversible, meaning the geophysical boundary will shallow and remain shallow.

Physical property variations

The delineation of the geophysical Moho requires that there are measurable differences in physical properties across it. To a first approximation, the geophysical transition, primarily as delineated by the seismic *P*-wave velocity and associated density increase, is a measure of a rapid change in bulk composition (e.g., Knopoff 1967; Hynes and Snyder 1995; Rudnick and Fountain 1995). In Lithoprobe, the application of multiple techniques allows detection of different properties (e.g., V_p, V_p/V_s (where V_p is the *P*-wave velocity and V_s is the *S*-wave velocity), density, and anisotropy) at, and across, the geophysical Moho in several regions.

Some of the physical property changes that might be encountered across the Moho are as follows:

(1) Both compositional (mafic lower crust to peridotite below the Moho) and metamorphic phase variations (mafic granulite to eclogite) would result in appropriate *P*-wave velocity and density variations for those measured by seismic methods. However, in general, eclogitic rocks have slightly higher densities than ultramafic rocks (e.g., peridotites), whereas ultramafic rocks have slightly higher velocities (e.g., Rudnick and Fountain 1995).

(2) Compositional variations across the Moho may result in a coincident transition in rock strength. This is likely the case for a transition from mafic to olivine-dominant (peridotitic) rocks (Chen and Molnar 1983) as well as for mafic granulite to eclogite (Cook 2002).

(3) Laboratory measurements on rocks suggest that electrical conductivity will decrease at the transition between mafic and ultramafic rocks (e.g., Haak 1982); however, partial melt or grain size could change this dramatically (Spratt et al. 2008).

(4) The scales of heterogeneities may vary substantially across the Moho (e.g., Tittgemeyer et al. 1999). Within the crust, the scales of heterogeneities are commonly approximately the same magnitude as the seismic wavelengths ($\sim 10^2$ m); whereas in the mantle, the scales are 10^3 m or greater (Tittgemeyer et al. 1999).

How these physical changes, which are measured across the geophysical Moho, relate to the geological transition from crust to mantle may not always be clear. As will be apparent in subsequent sections, one of the most significant results from Lithoprobe is that the origin and nature of the Moho and crust–mantle transition vary from region to region and have to be analyzed on a case by case basis. For example, the traditional view has been that we measure the geophysical signature (as per Mohorovičić) and apply a geological interpretation onto that geophysical change. We can suggest now that, in some areas at least, the geophysical change is superimposed onto older features and that some geological features may continue from the lower crust to below the Moho.

Lithoprobe database

The continental-scale database that was acquired within the Lithoprobe program (Fig. 1) is unique in its magnitude and in its relative uniformity of parameters for data acquisition and processing. Throughout the time frame of the project (1984–2005), efforts were made to maintain high standards of data quality, as technological advances occurred to allow comparative analyses of datasets from different regions and different vintages. Although most seismic and magnetotelluric data were recorded by contractors, the acquisition, processing, and initial interpretations were monitored and carried out by a relatively small group of individuals, within which consistent communication was maintained.

Twelve individual surveys totaling >18 000 km of seismic-refraction data were recorded across Canada in the 10 transect areas (Fig. 2). Many of these profiles were collocated with regional reflection, electromagnetic, and gravity profiles to correlate properties observed by the different methods.

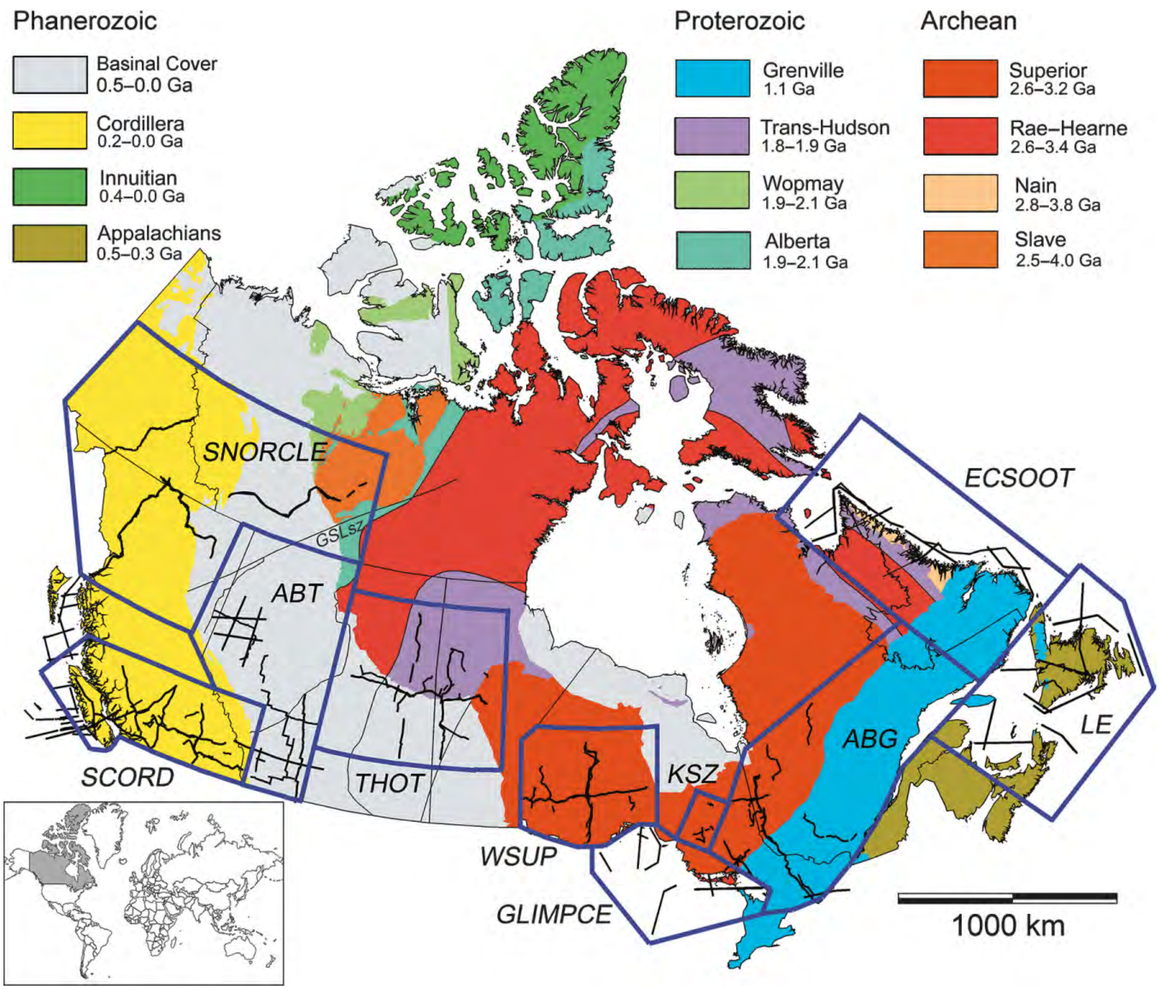
In addition to the refraction database, >12 000 km of land-based vibroseis and $\sim$10 000 km of marine airgun reflection data, as well as magnetotelluric data at $\sim$2000 locations, have been acquired across Canada in the Lithoprobe project since 1984 (Fig. 3). These data are located in regions with ages from Archean to Holocene, thus providing an opportunity to compare results for different geologic ages of crustal rocks. Although the data are generally very high quality, improvements in acquisition and processing have enhanced and sharpened images such that results acquired more recently provide greater resolution than earlier profiles. This in turn reduces the ambiguity of some relationships observed on earlier datasets.

Structure of the geophysical Moho

Regional variations

To illustrate the regional variations across Canada, maps have been compiled for the depth to the refraction Moho (Fig. 2) and two-way reflection times for the reflection Moho (Fig. 3). The depth to refraction Moho is simply the depth below sea level as measured along the series of refraction profiles recorded in the various transects.

Fig. 1. Map of Canada showing the locations of the major geological provinces and orogens, the 10 Lithoprobe transect areas (outlined areas), and the positions of seismic-refraction and seismic-reflection profiles (black lines). SNORCLE, Slave – Northern Cordillera Lithospheric Evolution; SCORD, Southern Cordillera; ABG, Abitibi–Grenville; ABT, Albert Basement Transect; ECSOOT, East Coast Seismic Onshore–Offshore Transect; GLIMPCE, Great Lakes International Multidisciplinary Program for Crustal Evolution; GSLsz, Great Slave Lake shear zone; KSZ, Kapuskasing Structural Zone; LE, Lithoprobe East; THOT, Trans-Hudson Orogen Transect; WSUP, Western Superior. Lines offshore west of SCORD are data recorded by the Geological Survey of Canada and incorporated into the SCORD interpretations. Inset map shows Canada in relation to the world.

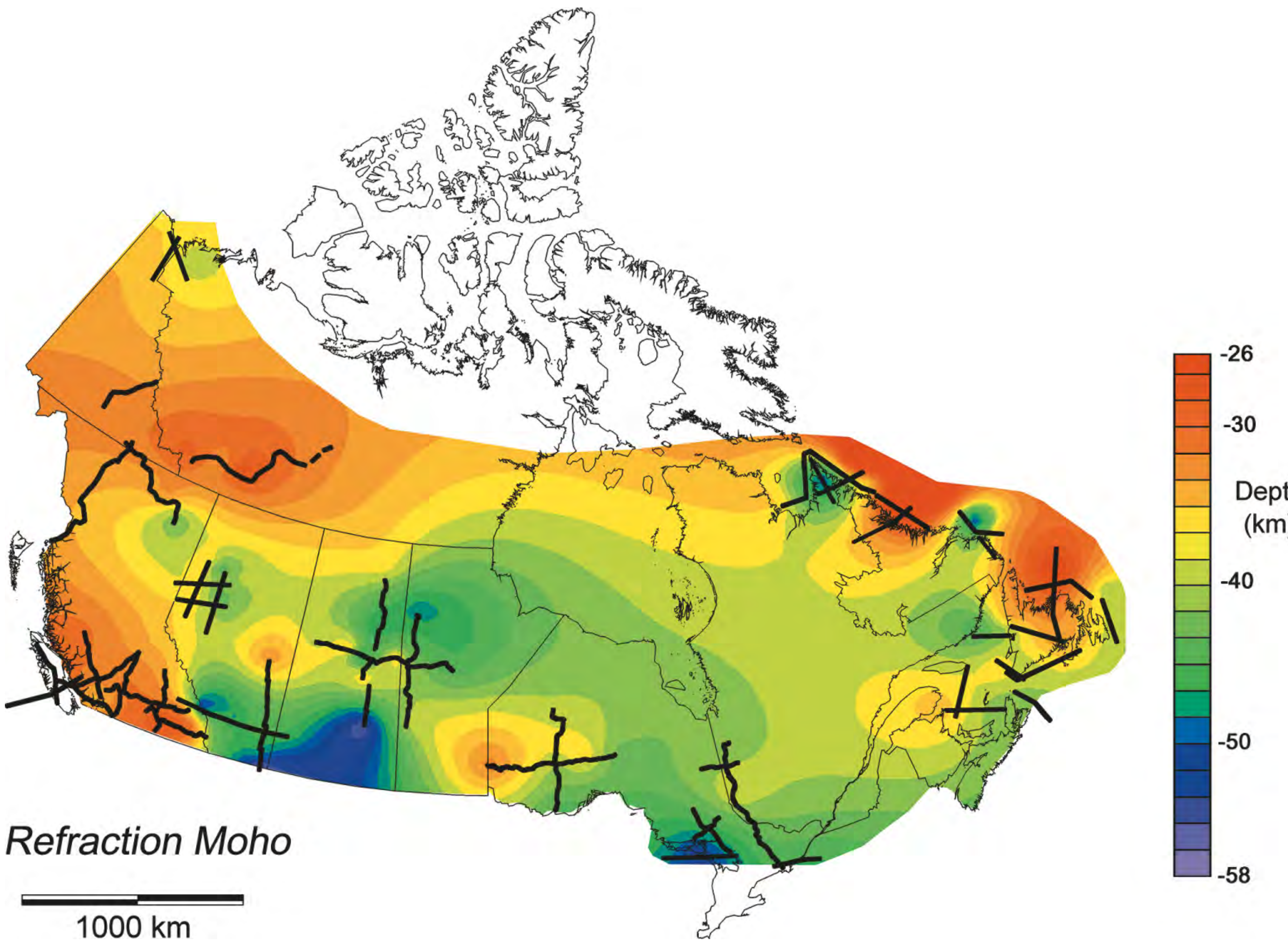


The reflection times for the reflection Moho required somewhat more effort to compile regionally consistent values from transect to transect. When processed, reflection data are related to an elevation datum that is usually near the surface. Accordingly, profiles recorded at high elevations (e.g., in the Cordillera) will typically be corrected to a relatively high datum, whereas those data recorded near sea level will have an elevation datum that is also near sea level. This means that, to compare different reflection datasets, the reflection times have to be adjusted to a common elevation, sea level in this case. While most of the adjustments are relatively small (<0.25 s), a few are up to 1.0 s.

The resulting maps of refraction depth and reflection times are presented in Figs. 2 and 3. It is to be expected that there are some general similarities between the two maps because, to some extent, the position of the reflection Moho depends on the location of the refraction Moho (i.e., it is the base of the deepest reflections from depths estimated from other geophysical methods). However, where coincident refraction and reflection lines have been obtained (e.g., Western Superior, Lithoprobe East, SNORCLE), the position of the reflection Moho (if visible) and the refraction Moho are close (i.e., reflections are observed at appropriate reflection travel times for depths to the refraction Moho), particularly for average crustal *P*-wave velocities of ~6.2–6.5 km/s (e.g., Cook 2002). For example, both maps show that the Moho is regionally shallow beneath much of the Cordillera, beneath Canadian Shield north of the Great Slave Lake shear zone (GSLSZ; Fig. 1), and along the eastern seaboard. Elsewhere, the refraction Moho is generally deeper than ~38 km, with travel times >~12.5 s, although some local variations are observed.

Significantly, within the Canadian Shield, there appears to be little correspondence between depth, or travel time, to the Moho and the age of the rocks on the surface (Figs. 1–3). Some of the greatest depths and longest travel times to the Moho are located in the Archean Superior Province and Medicine Hat block (southern Alberta), but comparable fea-

Fig. 2. Map of the depth to the refraction Moho (contour interval = 2 km) for the same area as in Fig. 1. Locations of the seismic-refraction profiles recorded during the Lithoprobe program along with the addition of some related profiles are indicated by the black lines. The non-Lithoprobe profiles include the Mackenzie Delta in northwest Canada (O'Leary et al. 1995), the Peace River Arch experiment (Zelt and Ellis 1989), a regional east–west profile in Alberta (Chandra and Cumming 1972), and several profiles in the offshore region of the Atlantic margin (e.g., Keen et al. 1986; Marillier et al. 1989). The map was constructed by picking refraction depths along each interpreted profile and then applying an automatic contouring program to produce the map. The map has a much higher spatial resolution than global models such as CRUST5.1 (Mooney et al. 1998). It is more reliable for Canada than models such as CRUST2.0 (Bassin et al. 2000), which do not utilize the Lithoprobe dataset, and it is similar to the recent LITH5.0 model, which included the Lithoprobe data and used spherical splines for interpolation (Perry et al. 2002).



tures are observed within the Trans-Hudson Orogen (Mesoproterozoic) and the Grenville Province (late Mesoproterozoic). Similarly, relatively shallow depths (<35 km) and short travel times (<11.5 s) to the Moho are observed in the Archean Slave Province, the Mesoproterozoic Wopmay Orogen, and the Mesozoic–Tertiary Cordillera.

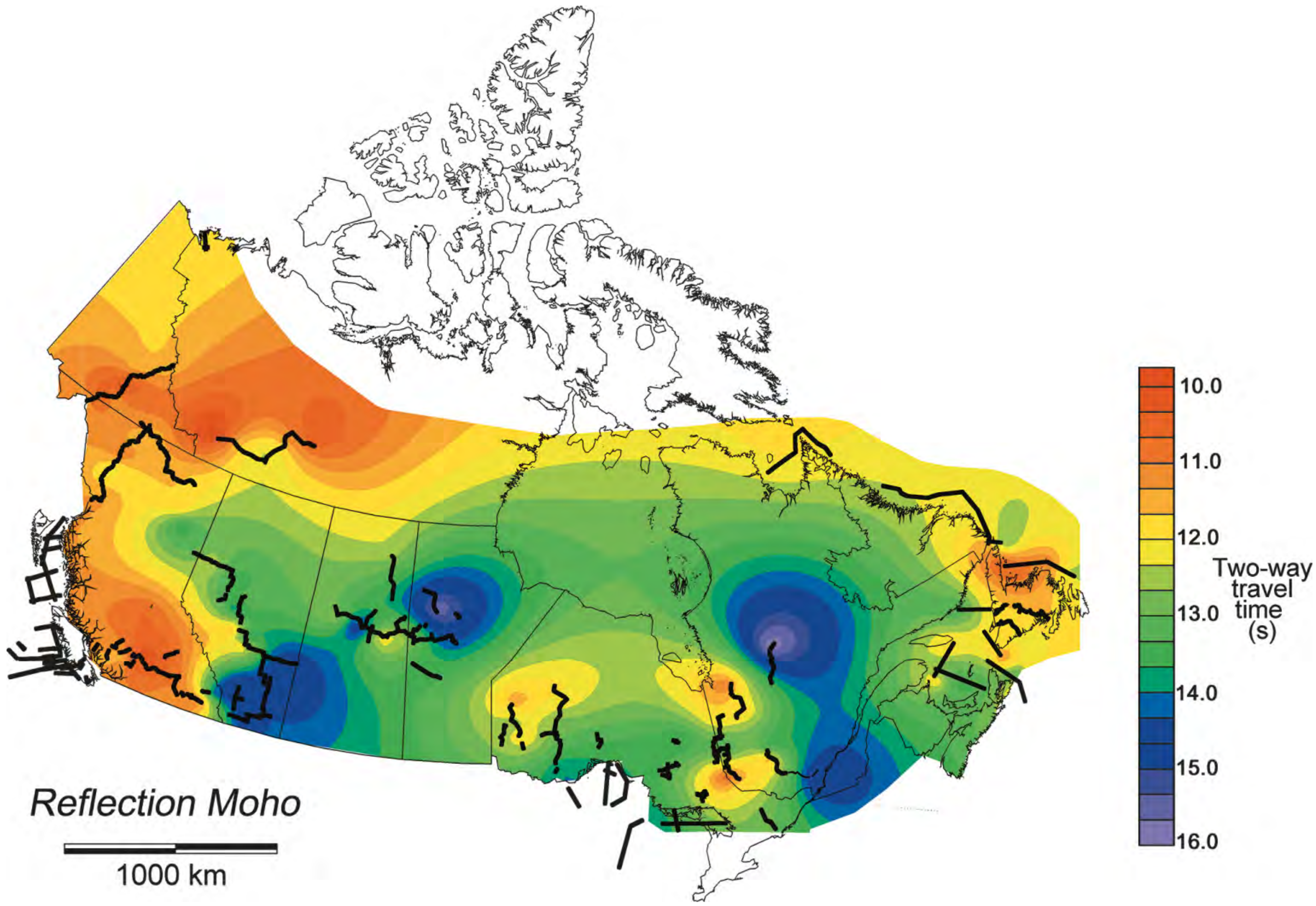
Thus, while the depth to the continental geophysical Moho is relatively uniform across Canada from the east coast to the west, some local variations are substantial. Nevertheless, only rarely, and then only locally, is it found at depths <30 or >55 km. Indeed, in some areas (e.g., SNORCLE transect), the depth to the geophysical Moho varies between only 30 and 40 km over a distance of >1500 km. This is an important observation because any interpretation of the origin of the geophysical Moho must account for uniformity of depth to the boundary, irrespective of billions of years of geological upheaval and complex lithospheric interactions, at the same time allowing for local depth variations of 20%–30%. Descriptions of variations within each of the transect regions follow.

Lithoprobe East

Lithoprobe East focused on the Appalachian Orogen in and around Newfoundland (Fig. 4). Here, the zonation of the orogen (Williams 1964) includes the externides of the Humber Zone (the rifted margin of ancient North America, Laurentia) and the Avalon Zone, the internides of the Dunnage Zone (remnants of the Iapetus Ocean and its margins), and the Gander Zone, a microcontinental block from the southern side of the Iapetus Ocean. It was the closure of the Iapetus ocean and subsequent continental collision that generated the Appalachian Mountains.

The Moho below the Appalachians of Newfoundland and the adjacent seas shows some variability in character and depth and has varying relationships to reflection fabrics in lower crust and mantle. The depth of the Moho has been

Fig. 3. Map of the travel times to the reflection Moho (contour interval = 0.33 s) for the same area as in Fig. 1. Locations of most reflection profiles recorded during the Lithoprobe program along with the addition of some related profiles are shown as black lines. The non-Lithoprobe profiles include the Mackenzie delta in northwest Canada (Cook et al. 1987), the Ahbau Lake profile in central British Columbia (Mair and Lyons 1976), and several profiles in the offshore region of the Atlantic margin (Marillier et al. 1994). The times are all related to sea level by calculating the static shift between the elevation datum of each profile and sea level.



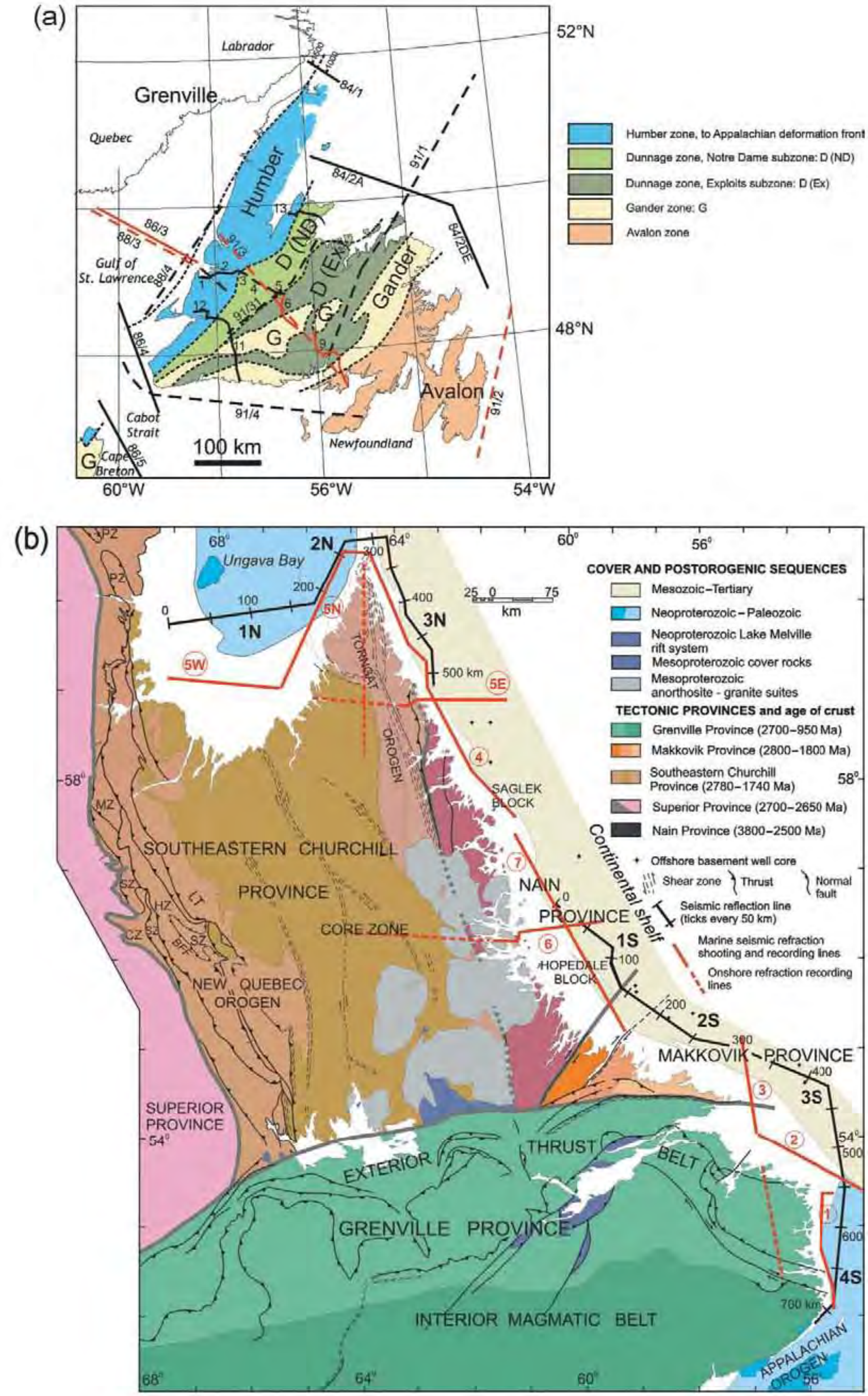
well defined from wide-angle seismic experiments (e.g., Hughes et al. 1994). It tends to be lower (shallower) within the orogen (~30–35 km) than within the Grenville Orogen to the northwest (~40–45 km) or the Avalon Zone to the southeast (~40 km), which is illustrated in Fig. 5. Departures from this simple conclusion (thicker crust below the Magdalen basin in the Gulf of St. Lawrence and thinner crust offshore northeastern Newfoundland) have been attributed to late Appalachian extension and magmatic underplating in the Carboniferous.

The thin crust below the Appalachians may reflect isostatic adjustments in the mantle part of the lithosphere, and the deeper mantle lithosphere is not well characterized in this region. A modest variation in mantle density could explain the thinner crust: the 10 km difference in crustal thickness could be caused by a zone of that thickness with a density ~50 kg m^{-3} lower in the lithospheric mantle below the Appalachian Orogen. Allied to such a possibility is the notion that the Appalachian Orogen was never excessively thick in this area because it resulted from a moderately soft collision with modest crustal thickening. This is very likely in central and northeast Newfoundland, where low-grade rocks are widely preserved within the orogen, but somewhat less likely in southwest Newfoundland and the Maritimes, where metamorphic grades are somewhat higher and granites sweated out from thicker crustal roots are more pervasively intrusive into the upper crust.

An alternative explanation of the thin crust below the Appalachians is eclogitization of mafic lower crust so that it now assumes the seismological character of mantle rocks (high V_P, low reflectivity). This has been suggested to explain mantle reflections in various places (e.g., Hynes and Snyder 1995), including offshore northeastern Newfoundland (Chian et al. 1998), and explain thin crust and Moho truncation of lower crustal reflections in southern Newfoundland (reflection profiles 89/6 and 86/9) by Van der Velden et al. (2004), though the truncation issue is problematical, as described later in the paper.

The reflection Moho is very well defined over profiles 89/6 and especially 89/9 in southern Newfoundland (Fig. 6; Hall et al. 1998) and correlates well with the wide-angle Moho. The reflection Moho here links narrow zones of strong reflectivity, which extend laterally in 10–20 km segments (above "A," Fig. 6), to a well-defined base of crustal reflectivity. The lower crust has a strong northwesterly dipping fabric that appears to sole towards the Moho, though Van der Velden et al. (2004), from their reprocessed data, considered that the dipping fabric is more likely truncated by the reflection Moho.

Fig. 4. (*a*) Geological map of the Lithoprobe East transect region (Hall et al. 1998), showing the major geological provinces and locations of seismic-refraction (broken lines) and seismic-reflection (solid lines) profiles. Red lines are those shown in Figs. 5, 6, and 7. *(b)* Geological map of the ECSOOT region (Hall et al. 2002), illustrating the major geological provinces and locations of seismic-refraction (red lines) and seismic-reflection (black lines) profiles.



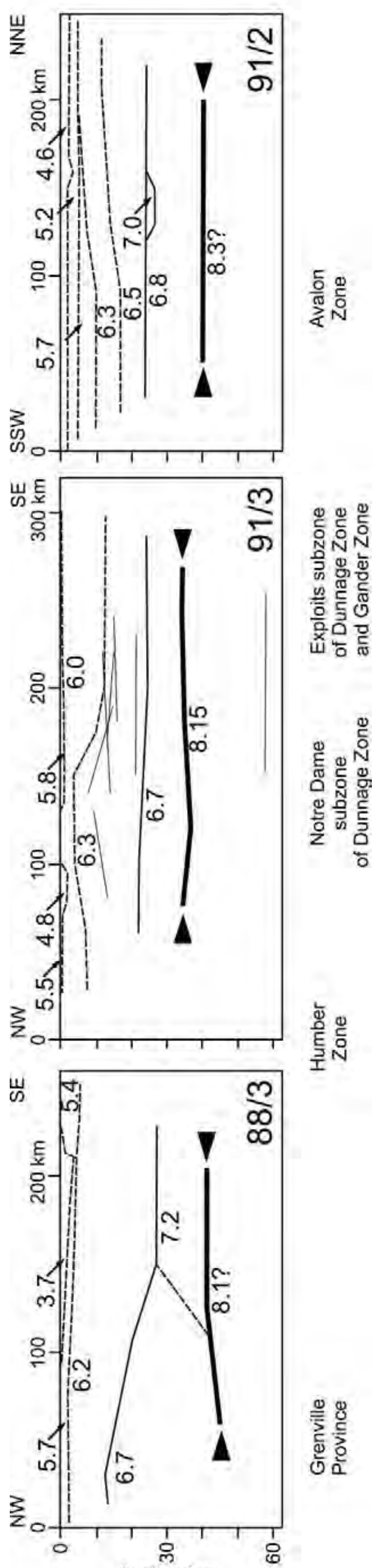


Fig. 5. Summary of wide-angle seismic-velocity models across the Appalachians of Newfoundland (extracted from fig. 2 of Hall et al. 1998), based in turn on Jackson et al. (1998) for profile 88/3, Hughes et al. (1994) for profile 91/3, and Marillier et al. (1994) for 91/2. Numbers indicate *P*-wave velocities in km/s. Arrow heads and thick lines accentuate the Moho, showing its shallowing into the orogen. Profile locations are shown in Fig. 4*a*.

These two interpretations lead to differing geological implications. Hall et al. (1998) suggested the fabrics relate to collisional compressional strains detaching at the Moho in a pattern familiar from numerical models of compressional orogens (Quinlan et al. 1993). Van der Velden et al. (2004) proposed that the fabrics link to a northwest-dipping feature in the mantle farther to the west that might be a relict subduction zone. They also concluded that the truncation of the dipping fabric by the Moho reflection indicates that the latter is a younger structure cutting across the earlier dips and perhaps related to the top of a zone of eclogitization of mafic crustal material now in the seismological mantle.

The marginal structures of the Appalachian Orogen may include underplating of the rifted Laurentian margin, interpreted from high-velocity, strongly reflective lower crust below the Humber Zone (Fig. 7; Marillier et al. 1989). Here, the Grenville Province is characterized by a mid-crustal reflection fabric with southeasterly dip and is likely pre-Appalachian (Grenvillian) in age (Fig. 7). The reflections appear to flatten into a low-reflectivity zone in the lower crust. The Moho lies below a deeper 2 s thick reflective zone cut by northwest-dipping fabrics that extend into the mantle (Fig. 7). The top of the wedge of high-velocity, high-reflectivity lower crust, interpreted as an underplate, is one reflection package that may dip down into the mantle, implying that these structures might be associated with Appalachian (postunderplate) deformation. If this were the case, the deep crustal deformation associated with the orogen extends further into the Laurentian hinterland than the surface deformation (Fig. 4).

Eastern Canadian Shield Onshore–Offshore Transect (ECSOOT)

The Eastern Canadian Shield Onshore–Offshore Transect focused on the Proterozoic accretion of Archean and more juvenile crustal blocks onto the northeastern edge of the Canadian Shield (Fig. 4*b*). Paleoproterozoic orogens welded the Archean Nain Province onto the Superior Province with the southeastern Churchill Province caught between; and the juvenile arcs of the Makkovik Province stitched to the Nain Province at about the same time. Slightly younger events created the Labradorian block of the easternmost Grenville Province. After relative quiescence during the Mesoproterozoic (except for the massive intrusive episode associated with the Nain Plutonic Suite), Neoproterozoic orogenesis completed the building of the Canadian Shield by adding the Grenville Province to its southeastern edge.

A Paleoproterozoic crustal root lies below the Torngat Orogen in northern Labrador. The root is best seen on wide-angle seismic models of ECSOOT lines 5E and 5W (Fig. 8; from fig. 5 of Hall et al. 2002, which in turn is based on Funck and Louden 1999). The depth of the preserved root is ~50 km beneath the Torngat Orogen, or ~15 km deeper than the average of 35 km in adjacent areas (Fig. 8).

Tomographic inversion of the wide-angle Moho reflection (PmP) travel times provided an areal view of the root, which mimics the Bouguer gravity (fig. 9 from Funck et al. 2000). Together, the two indicate that the root is partly bounded by the Abloviak shear zone and its westerly extension into Ungava Bay, suggesting that the root formed in relation to these Paleoproterozoic structures that played a major role in

Fig. 6. Illustration of lower crustal fabrics and reflection Moho from profiles 89/6 and 89/9 below the Dunnage (Exploits subzone) and Gander zones of the Appalachian Orogen in central and southern Newfoundland, taken from fig. 1 of Hall et al. (1998). Broken lines are layer boundaries taken from models of near-collinear wide-angle seismic profiles. Numbers indicate *P*-wave velocities in km/s. Section is at true scale for *P*-wave velocity of 6 km/s. Lower box shows lower crust and Moho at expanded scale. A, B, and C identify features described in text. For location, see Fig. 4. LE, Lithoprobe East transect.

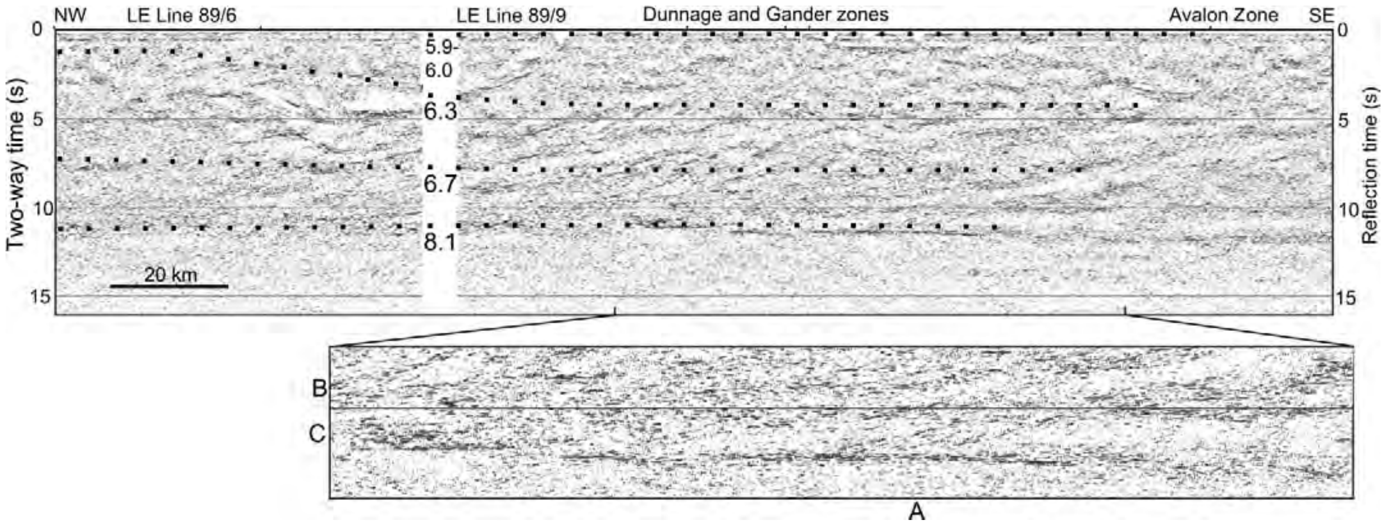
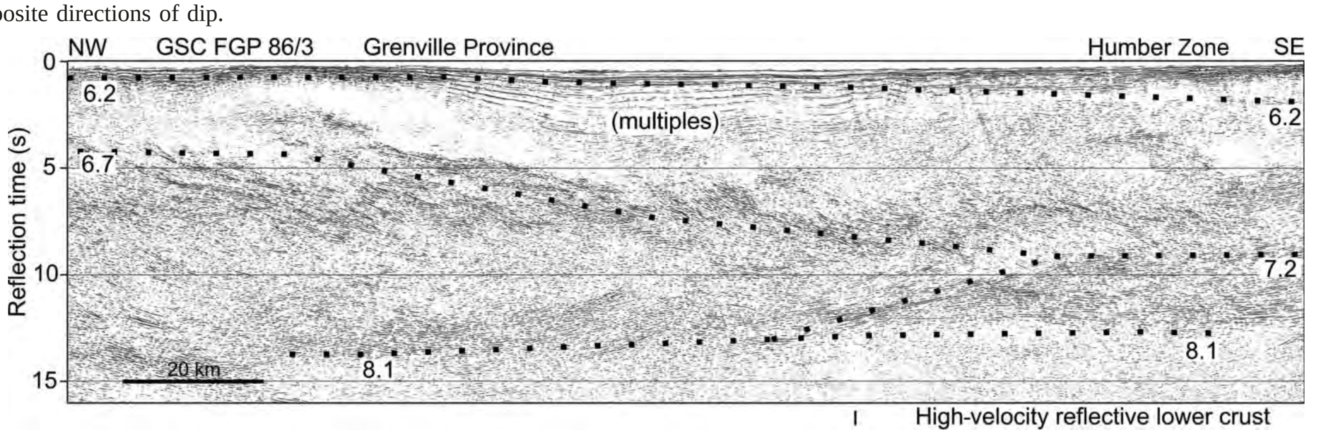


Fig. 7. Illustration of marine seismic-reflection profile Geological Survey of Canada Frontier Geoscience Program (FGP) 86/3, overlain with velocity model from coincident wide-angle seismic profile (broken lines indicate layer boundaries; numbers indicate *P*-wave velocities in km/s). Note the strong lower crustal reflection fabric below Humber Zone and strong reflection fabrics in mid- and lower crust that have opposite directions of dip.



the indentation of the Superior and Nain provinces by the southeastern Churchill Province (Wardle et al. 2002). The root is ∼15 km in depth extent, ∼80 km across, and >200 km long. It is possible that it extended farther south at one time but fades towards the Nain Plutonic Suite, the thermal influence of which in Mesoproterozoic time may have caused the root to relax.

Lower crustal and Moho reflectivity are not apparent for the Archean part of this area that was unaffected by later Proterozoic deformation. Variable reflectivity in the lower crust and at the Moho is observed in the areas affected by Proterozoic deformation. Inwardly dipping crustal reflection fabrics characterize the Makkovik Province. Juvenile Paleoproterozoic arcs are underlain by northwest-dipping, mid- and deep-crustal reflections that appear to flatten near the level of the Moho, as identified from wide-angle seismic-velocity models. In this region, deep, dipping crustal reflection packages are thought to originate most often from ductile shear zones. They sole at, or very close to, the Moho, which does not display a prominent reflection (Kerr et al. 1997). The area has a complex history, and subduction switches and rollbacks (as described by Kerr et al. 1997) may be only a small part of the history that is discernable today.

Prominent, intersecting lower crustal and mantle reflection fabrics characterize the southern margins of the southeastern Grenville Province (Fig. 10; Hall et al. 2002). Labradorian deformation mapped at surface indicates outwardly verging thrust systems. The mid-crustal reflection fabrics confirm that such structures extend to the lower crust, in a pattern of crosscutting blocks. Very strong reflection fabrics are observed in the deep crust and extend into the mantle. Fabric S1 (Fig. 10) runs from subhorizontal origins at the top of the lower crust, dips through the base of the crust (as estimated by extrapolation from wide-angle profile ECSOOT 2), and flattens at that level before dipping

Fig. 8. Wide-angle seismic-velocity model across the Torngat Orogen along lines 1N, 2N, and 3N, showing a 70 km wide, 10–15 km deep, crustal root below the orogen (redrawn from Funck and Louden 1999). For location, see Fig. 4*b*. LLC, Lac Lomier complex; TD, Tasiuyak domain.

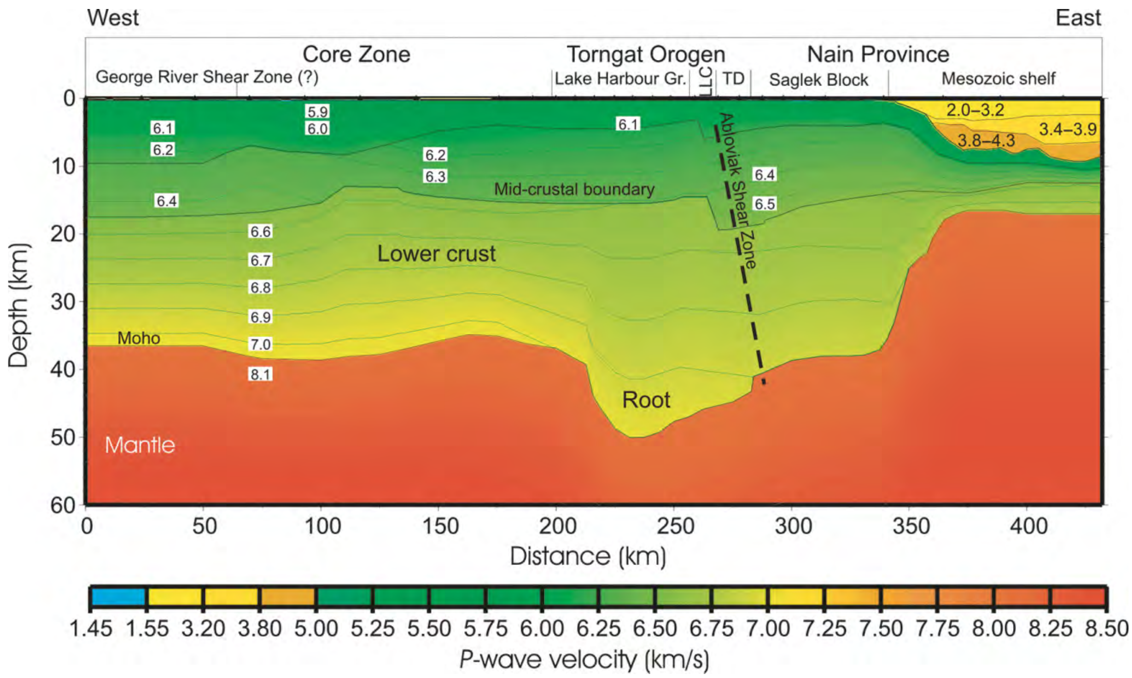
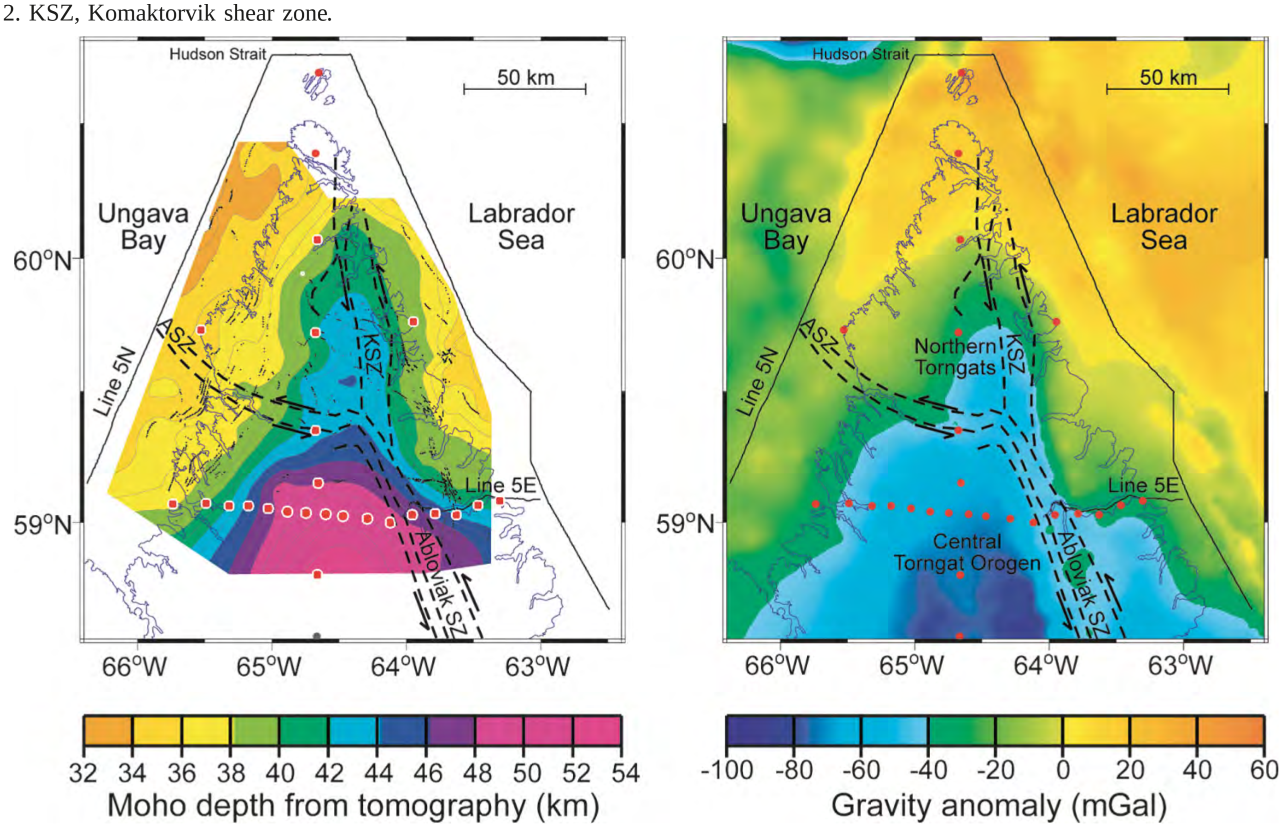


Fig. 9. Crustal root of the Torngat Orogen (redrawn from Funck et al. 2000). Left-hand map shows Moho contours from tomographic inversion of wide-angle Moho reflection; right-hand map shows Bouguer gravity of same region. Red dots show land seismographs that recorded offshore airgun signals used in the inversion. Bouguer gravity appears to be a viable proxy for Moho depth in this region. Crustal root is constrained by bend in the Torngat Orogen associated with the Abloviak shear zone (ASZ). Compare with the northeastern portion of Fig. 2. KSZ, Komaktorvik shear zone.



off the base of the section into the mantle. A fabric with similar mantle dip occurs immediately above S1 at the eastern end of the section (fabric S2, Fig. 10). There is no direct measurement of the depth to Moho at this end, except for a zone of horizontal reflectivity cutting through S1 at ∼14 s reflection time, and a base of strong deep reflections at 13 s reflection time (“Ml”, Fig. 10). Note that, in turn, S2 is truncated by the extensive and strong reflection fabric at Mu.

Abitibi–Grenville

The Abitibi–Grenville transect region encompasses the Archean tectonic assemblages of the Abitibi Province, post-assembly modification of the Abitibi by Proterozoic tectonism, and the Mesoproterozic development of the Grenville Orogen (Fig. 11). The first Lithoprobe transect, the Kapuskasing Structural Zone, and the Great Lakes International Multidisciplinary Program for Crustal Evolution (GLIMPCE) profiles are associated with the Abitibi–Grenville transect and are included here. The Abitibi–Opatica belts are part of the Superior craton but are considered separately here from the Western Superior transect, as discussed later in the paper.

The crust is generally thinner within the Archean Abitibi portion of the Superior Province (32–40 km) than it is beneath the Grenville Province (42–46 km) (Fig. 12; Grandjean et al. 1995; Winardhi and Mereu 1997; White et al. 2000). The refraction Moho is diffuse and characterized by a 5–7 km thick zone with a velocity gradient and lateral velocity variations, rather than a sharp discontinuity (Winardhi and Mereu 1997; Mereu 2000). No seismic-refraction data are available across the Opatica domain. However, Telmat et al. (2000) interpreted a –30 mGal gravity anomaly in the northern Abitibi and Opatica domains as a ∼6.5 km thick crustal root in which the thickness of the crust increases from a 37.5 km regional thickness to a local thickness of 44 km (Telmat et al. 2000).

Seismic-reflection data were acquired across the Wawa gneiss of the Kapuskasing Structural Zone and indicated that the gneiss is highly reflective (e.g., Percival and West 1994). The listric character of the reflections in the Abitibi and Opatica reflection profiles (Fig. 13) is consistent with the orientation of structures in the Wawa gneiss of the Kapuskasing Structural Zone; thus, it is likely that rock types similar to those in the Wawa gneiss are present beneath the northern Abitibi (Opatica). As a result, the lower crust of the Opatica belt is likely a result of north-directed underthrusting and tectonic underplating. Thus, the structures in the middle and lower crust are likely younger than those at the surface, and the surface features are structurally decoupled from those in the middle crust.

The underthrusting of the southern Abitibi belt rocks northward beneath the Opatica belt may be responsible for the apparent difference in character of the reflection Moho between the southern (Abitibi) and northern (Opatica) portions of the seismic profile in Fig. 13. Here, the reflection Moho of the Opatica belt is sharp and relatively flat, perhaps partly due to structural flattening in the lower crust. In contrast, the reflection Moho beneath the southern (Abitibi belt) portion of the line is much less distinct.

In the southwestern Grenville Province of Ontario and

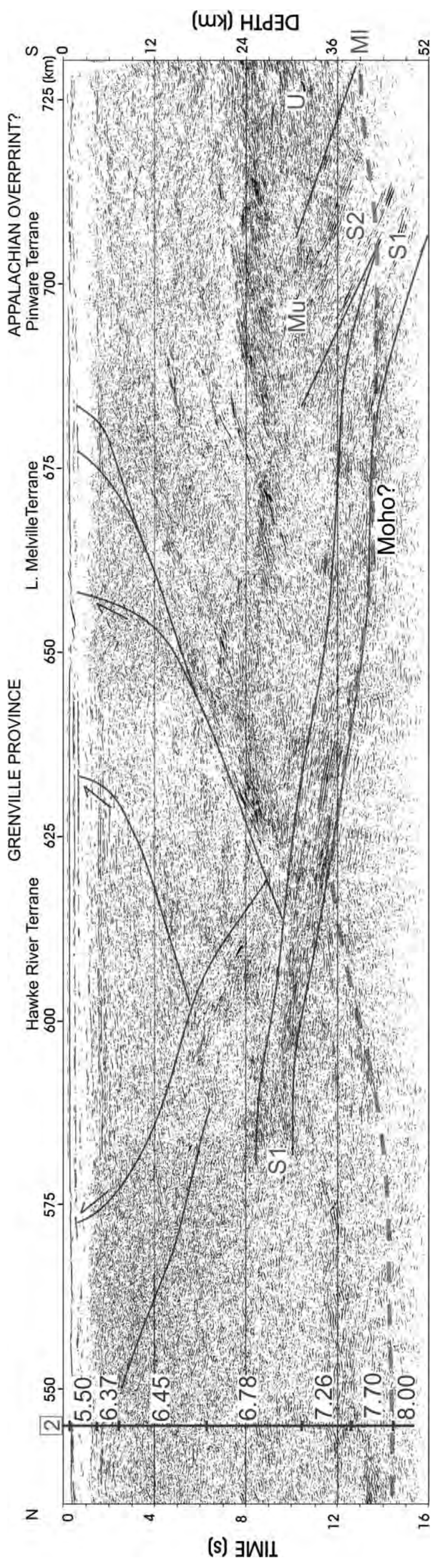
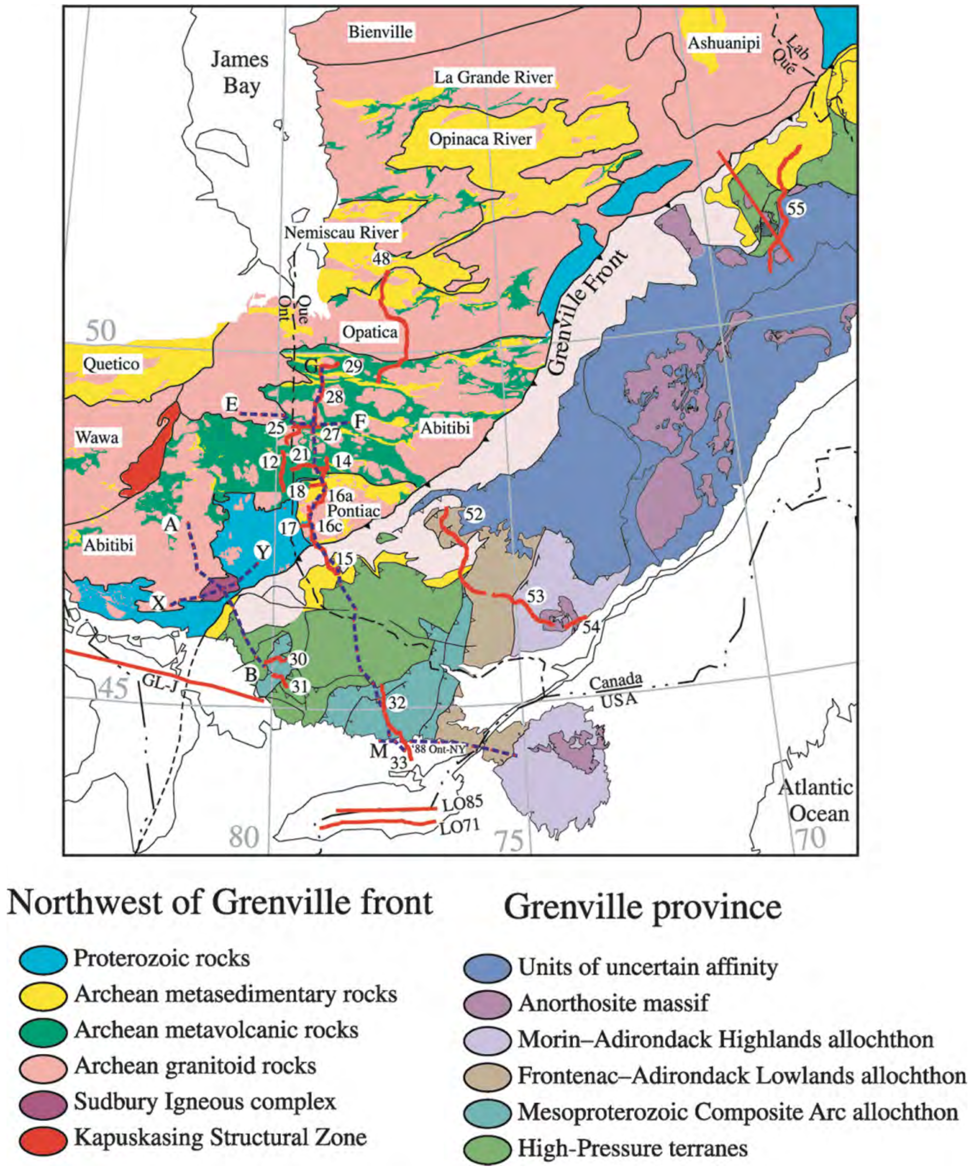


Fig. 10. Seismic-reflection profile 4S (Fig. *4b*) across the Grenville Province (taken from fig. 4 of Hall et al. 2002), showing (in thin black lines) asymmetrical distribution of inward-dipping crustal fabrics, opposing dip in mantle reflections and no obvious reflection signal from the Moho. Broken line shows inferred location of Moho from wide-angle seismic-velocity models from profiles 2 and 1 (Fig. *4b*). Column 2 on left side gives 1-D velocity values (km/s) from profile 2 after converting depths to two-way traveltimes. Mu, strong-reflection fabric above Moho; U, strong-reflection fabric above S2; S1, dipping fabric described in text; S2, dipping fabric truncated at Mu as described in text.

Fig. 11. Map of the Abitibi–Grenville transect region with seismic-refraction lines (broken lines) and seismic-reflection lines (red lines; white circles indicate reflection line numbers) indicated (modified from Ludden and Hynes 2000).

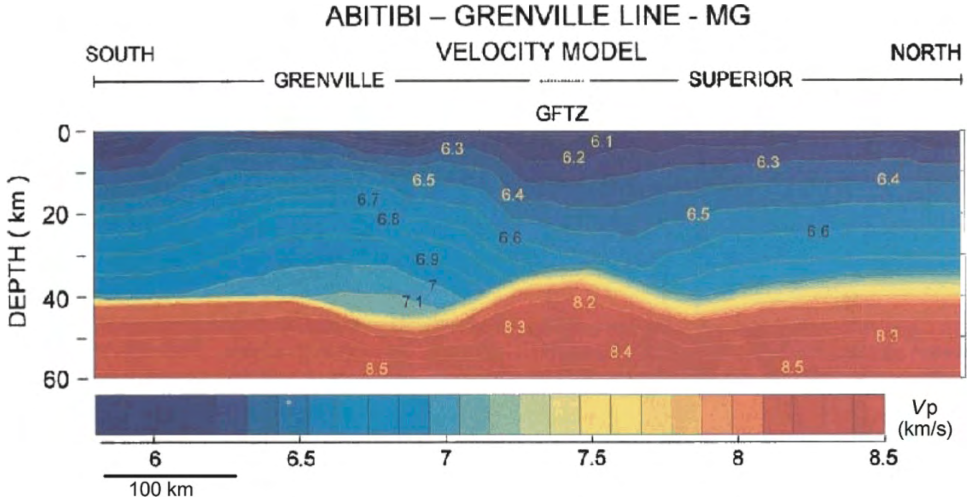


Quebec and adjacent parts of the Midcontinent Rift, significant crustal thickness variations are documented by Lithoprobe studies. These variations generally correlate with large-scale tectonic belts but are not expressed by surface topography and are often poorly correlated with gravity anomalies. The thickest crust in the region (up to 55 km) is observed beneath the central graben of the 1.1 Ga Midcontinent Rift beneath Lake Superior (Shay and Tréhu 1993). This zone of anomalous crustal thickness is flanked by much thinner crust (35–40 km) at the margins of the rift. Despite the extreme thickness of the crust, the rift is marked by a positive gravity signature that reflects the voluminous package of dense basaltic rocks that forms most of the crustal section (Mariano and Hinze 1994).

To the east, the Grenville Front in southern Ontario marks a transition from thicker crust (up to 45 km) within the Mesoproterozoic Grenville Orogen to significantly thinner crust ($\sim$35 km) in the Superior Craton (Fig. 14; Winardhi and Mereu 1997; White et al. 2000). Unlike the unusually thick crust found beneath the Wyoming Craton of western North America (Gorman et al. 2002), the zone of thickened crust in the Grenville does not appear to be associated with any high-velocity lower crustal layer (Winardhi and Mereu 1997); the Grenville Front has subsequently been observed using data from a Lithoprobe teleseismic profile (Rondenay et al. 2000) and more recently using a regional deployment of portable seismograph stations (Eaton et al. 2006). The distribution of seismograph stations used in the latter investigation showed that the region of thick crust near the Grenville Front constitutes a keel that strikes parallel to the Front. The crustal thickness variations here are far in excess of requirements for local isostatic equilibrium (Eaton et al. 2006). This crustal root may be preserved as a result of processes that slowly reduce density contrast between the lower crust and upper mantle (Fischer 2002).

To the east, the Grenville Front crustal root terminates

Fig. 12. Model of refraction velocities along profile MG (see Fig. 11 for location) as interpreted by Winardhi and Mereu (1997). GFTZ is the location of the Grenville Front Tectonic Zone that dips southward at this location. The elevated velocities in the lower crust to the south of GFTZ have been interpreted to be associated with eclogites (Eaton 2006). V_p, P-wave velocity.



abruptly at the Ottawa–Bonnechere graben, which marks the western boundary of a region of relatively thin (30–35 km) crust and moderate seismicity (Eaton et al. 2006). The Grenville Front crustal root reappears and thickens toward the east, where it is expressed as a regional gravity low in eastern Quebec (Berry and Fuchs 1973; Eaton et al. 1995). In the Superior Craton north of the Front, northward-dipping mantle reflectors imaged by Lithoprobe reflection data are linked to a possible suture and have been interpreted as an upper mantle shear zone that was active during Archean subduction (Calvert et al. 1995). Despite the evidence for subduction, the Moho is relatively flat in the Superior Craton, with the exception of local deepening near the Kapuskasing structure (Boland and Ellis 1989; Darbyshire et al. 2007).

Western Superior

The western Superior Province was assembled during the interval 2.72–2.60 Ga by a sequence of at least five distinct large-scale accretionary events (Percival et al. 2006) resulting in the east–west trending ‘‘belt-like’’ pattern that characterizes the regional geology (Figs. 15*a*, 15*b*). The Moho and associated crust–mantle transition in the western Superior Province have been imaged by a variety of seismic methods, including near-vertical seismic-reflection profiling (White et al. 2003; Calvert et al. 2004), travel time – amplitude inversion and direct imaging using refraction – wide-angle reflection (R/WAR) data (Musacchio et al. 2004 and Kay et al. 1999, respectively), and P- and S-wave receiver functions (Angus et al. 2008). The depth to Moho varies by ~50% within the western Superior Province, ranging from 32 to >45 km (Fig. 15*c*). The thickest crust is observed in the south, to the north of the Midcontinent Rift system in Lake Superior (Fig. 15*c*), where it is associated with a northward-thinning, high-velocity lower crustal layer (V_p = 7.4–7.5 km/s). Crustal thickness decreases gradually northward toward the centre of the province where it flattens at ~38 km depth. The thinnest crust (32 km) is found in the westernmost part of the province where Calvert et al. (2004) have proposed late crustal-scale extension. A local minimum of ~36 km occurs beneath the Lake Nipigon region, which may be related to Mesoproterozoic rifting (Kay et al. 1999; Musacchio et al. 2004; Calvert et al. 2004).

Lower crustal properties and inferred rock compositions vary significantly across the western Superior Province. V_p and V_p/V_s range from 6.7 to 7.5 km/s and 1.72 to 1.86, respectively (Fig. 16*a*; Musacchio et al. 2004). An 8% azimuthal anisotropy is invoked for a distinct lower crustal zone (V_p = 7.4–7.5 km/s in the fast propagation direction, which is normal to the east–west regional geological strike; and V_p/V_s = 1.86) of inferred amphibolitic composition within the southern part of the province (Fig. 16*b*). The upper mantle velocities immediately beneath the Moho are generally high ranging from 8.0 to 8.3 km/s.

In general, as in most other regions, the reflection Moho observed on near-vertical-incidence reflection profiles across the western Superior Province (Fig. 17; White et al. 2003; Calvert et al. 2004; Van der Velden 2007) is defined by a relatively abrupt vertical transition from reflective lower crust to nonreflective upper mantle with or without an associated distinct reflection at the base of the reflective lower crust. Similarly, wide-angle reflection images show a prominent Moho reflection across the western Superior Province (Kay et al. 1999). The reflection Moho varies smoothly with only a few exceptions where zones of dipping reflectivity can be followed from the lower crust into the upper mantle to sub-Moho depths of 5–10 km. In at least one instance, a vertical offset of the Moho by 2–3 km occurs across one of these zones. These zones have been interpreted as suture zones associated with the original cratonic assembly (White et al. 2003) and can be traced to the middle or upper crust along low-angle trajectories.

Trans-Hudson Orogen

The Trans-Hudson Orogen (THO) is part of a North American network of Paleoproterozoic orogenic belts formed by crustal accretion and collision of older Archean continental blocks (Fig. 18; Hoffman 1988). However, it is the only component of the network that exposes a complete orogenic section characterized by a zone of Paleoproterozoic

Fig. 13. Foldout 1. Combined seismic-reflection profiles (lines 28 and 48; locations in Fig. 11) across the Abitibi–Opatica subprovinces of the eastern Superior Province (modified from Van der Velden 2007; see also Calvert et al. 1995). Note the prominent reflection Moho and the projection of reflections from the lower crust into the mantle. M, mantle reflection.

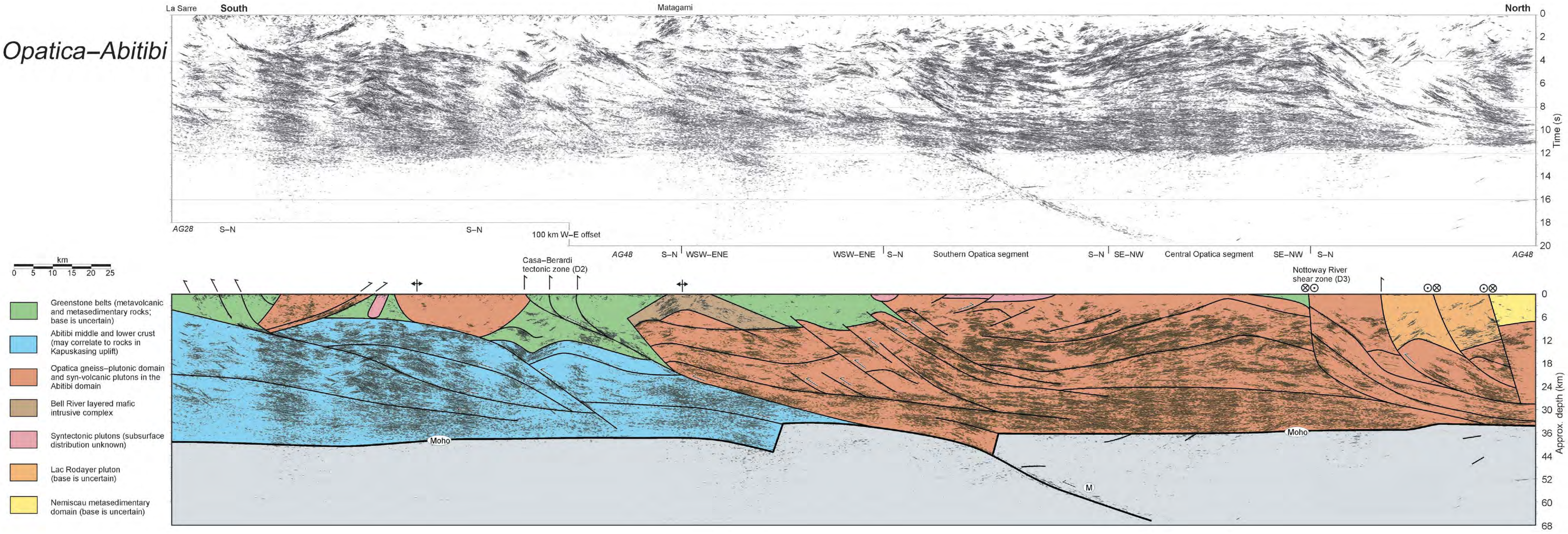


Fig. 14. Combined seismic-refraction model (top) and seismic-reflection data across the Grenville Front (GF; modified from White et al. 2000). Line locations are shown in Fig. 11. D, domain; GFTZ, Grenville Front Tectonic Zone.

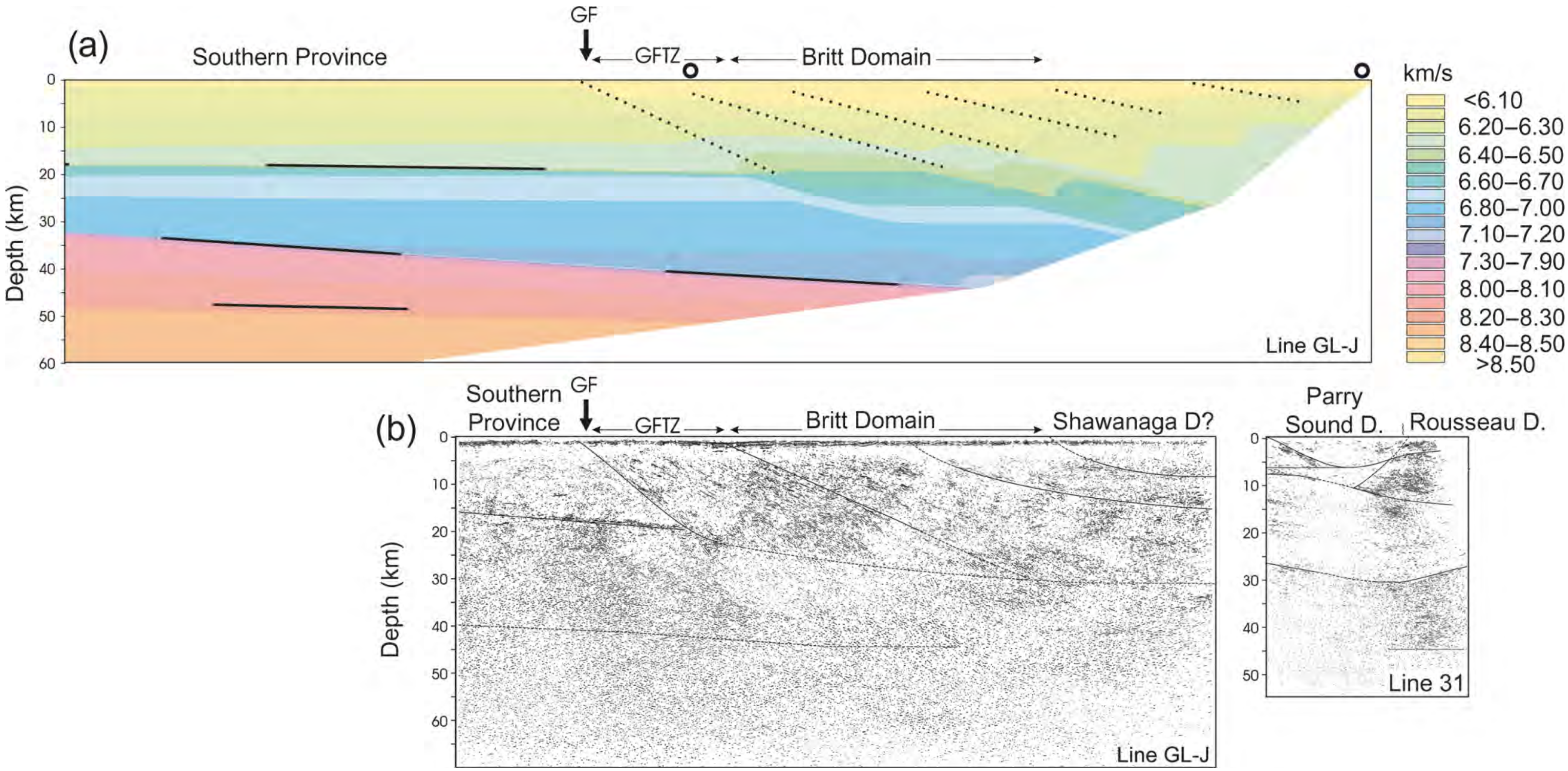
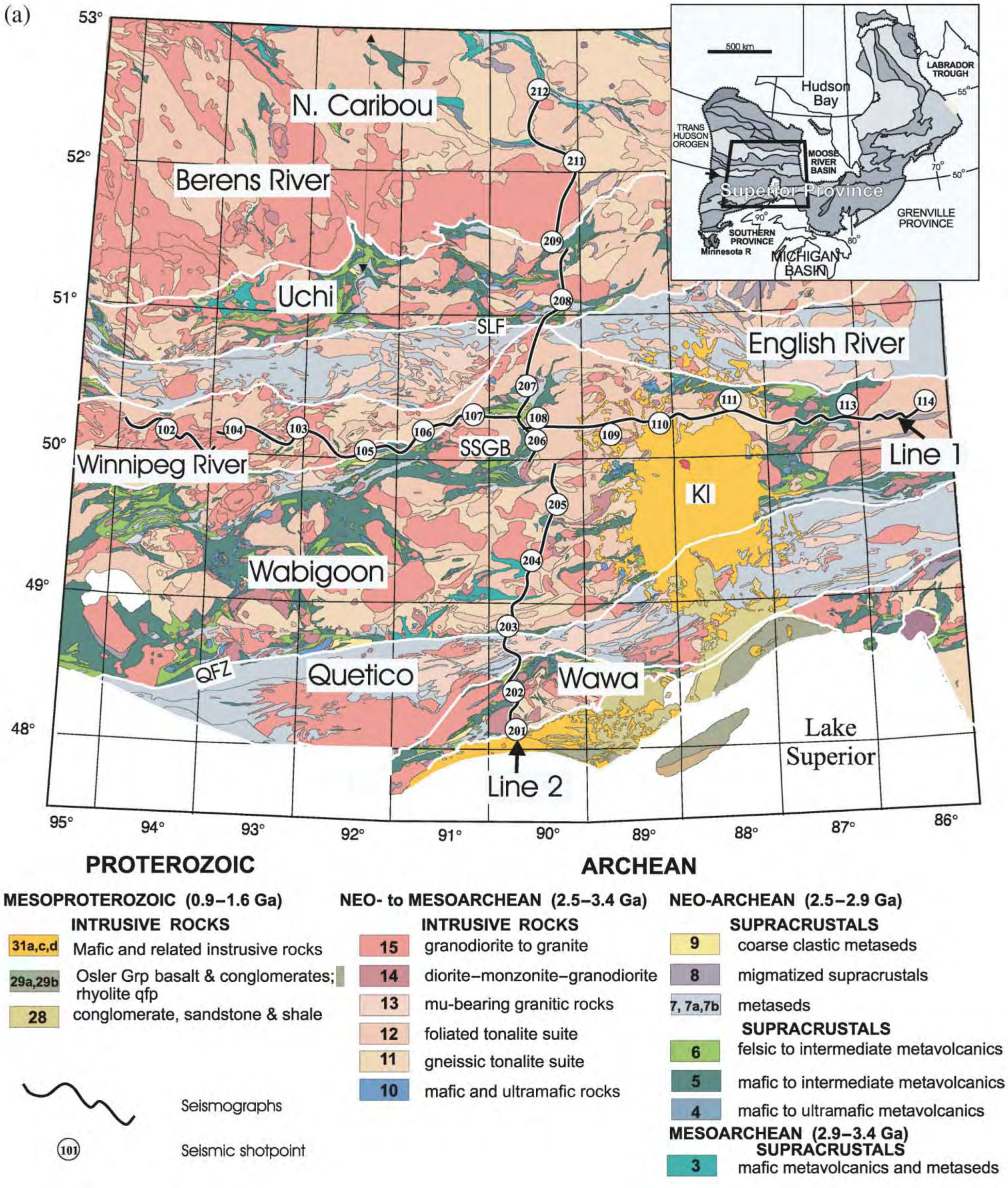


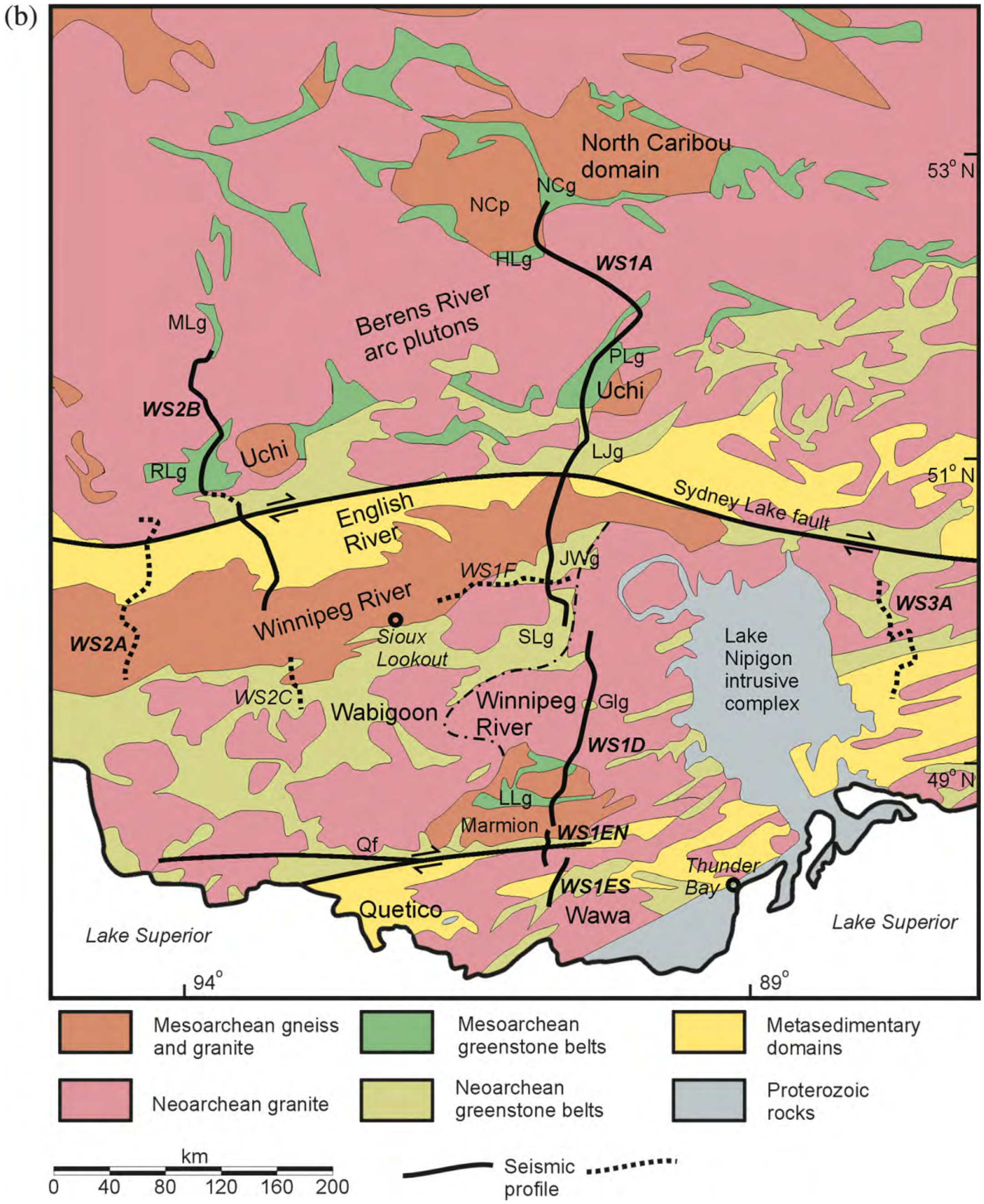
Fig. 15*a*. Map of the Western Superior transect region illiustrating the locations of seismic-refraction profiles 1 and 2 (modified from Musacchio et al. 2004). KI, Keewenawan intrusive complex; QFZ, Quetico fault zone; SLF, Sydney Lake fault; SSGB, Savant–Sturgeon greenstone belt.



(ca. 1.9–1.8 Ga) juvenile rocks sandwiched between variably reworked Archean continental blocks — the Hearne Craton to the northwest and the Superior Craton to the southeast. Recognition of the THO as a major orogenic belt dates back to the late 1970s and early 1980s; the volume edited by Lewry and Stauffer (1990) provides a comprehensive summary.

Until Lithoprobe, the prevailing view was that the Archean Superior Province extended beneath the THO. However, the 1991 reflection survey across the orogen

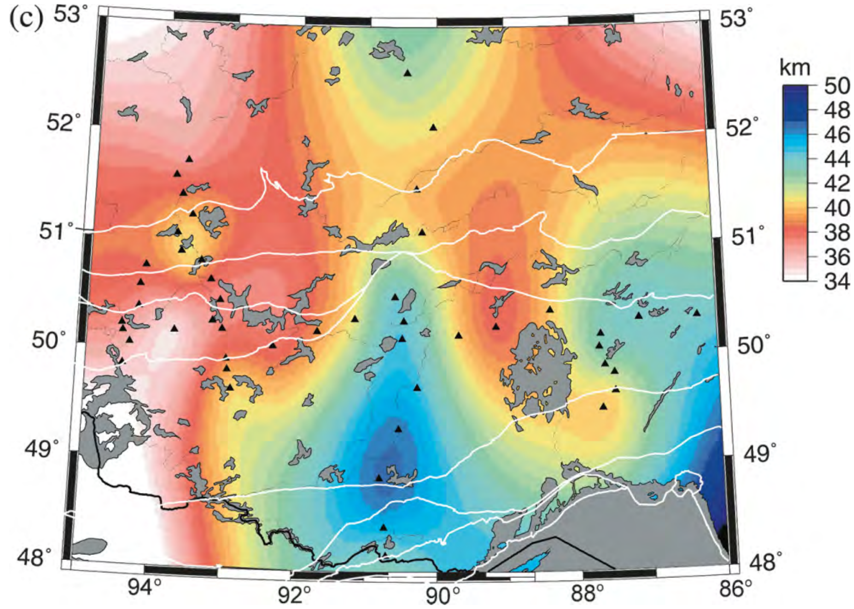
Fig. 15*b*. (*continued*). Map of the Western Superior transect region showing the locations of regional seismic-reflection profiles (modified from Van der Velden 2007).



unequivocally demonstrated that both the Superior and Hearne provinces are structurally isolated from the Reindeer zone and the Archean rocks are associated with a newly discovered Archean minicontinent, now called the ‘‘Sask craton’’ (Lucas et al. 1993, 1994; Lewry et al. 1994; Pandit et al. 1998).

Active-source seismic studies included a series of vibroseis reflection profiles, totalling ~2060 km, a coincident 200 km long east–west dynamite reflection profile in the western Reindeer zone and three long-range R/WAR lines, two ~750 km and one 500 km long, across and along the orogen (Fig. 18). Moho reflections from the near-vertical reflection data and the two phases, PmP and uppermost mantle refraction (Pn), from the wide-angle data demonstrated the existence of a crustal root within the Reindeer zone and enabled compilation of a map of the surface of the Moho (Fig. 20). This map shows the substantial variation in Moho depth, presumably associated with the collisional and post-collisional development of the orogen (Hajnal et al. 1996, 2005). The dynamite survey showed clearer Moho signatures than the vibroseis survey and included some dipping sub-Moho reflections that are likely related to collisional tectonics of the THO (Bezdan and Hajnal 1996). Interpretations of the reflection data, combined with analyses of the potential

Fig. 15*c*. (*concluded*). Map of the depth to refraction Moho in kilometres (includes *P*- wave receiver function data, as well as refraction lines 1 and 2; D. White, personal communication, 2008). The white lines represent the boundaries between domains shown in Fig. 15*b*.



field data for the region, enable the areal extent of the Sask craton to be mapped out (Fig. 20).

Interpretation of the long-range R/WAR data generated important results for the upper mantle; one of which is described here, and the second is described later within a different theme. Perhaps the most unusual feature of the interpretation is the identification of a limited region in the uppermost mantle in which high *P*-wave velocities, up to 8.6 km/s compared with the general value of ~8.2 km/s, are identified along lines R2 and R3, whereas relatively low velocities, ~8.1 km/s, are interpreted for the same region along line R1 (Fig. 19; Németh et al. 2005). Velocity anisotropy, probably due to lattice-preferred orientation of olivine in the mantle as a result of ductile flow, is believed to be the cause of the different velocities; but it is not clear why such anisotropy occurs over such a limited region. Németh et al. (2005) speculated that the anisotropy is the result of continental collisions, which formed a suture in the mantle lithosphere that is much narrower than the crustal or surface expression of the orogen (e.g., Davies and von Blackenburg 1995).

Assuming the fast velocity direction of the mantle anisotropy is parallel to the last increment of ductile flow (e.g., Zhang and Karato 1995), the latest deformation along the suture zone was an extension that was oriented approximately north-northwest – south-southeast. The extensional deformation could have been caused by a small counterclockwise rotation of the Superior plate in the central Trans-Hudson Orogen generated by continued northward movement of the main Superior plate further east (Németh et al. 2005). In the mantle, the rheologically weak suture zone accommodated most of the extensional deformation. In the weak lower crust, the extension was compensated by lower crustal flow; whereas in the brittle upper crust, north–south trending dextral strike-slip faults developed as a consequence of the north–south extension and continuing northwest–southeast compression (Németh et al. 2005).

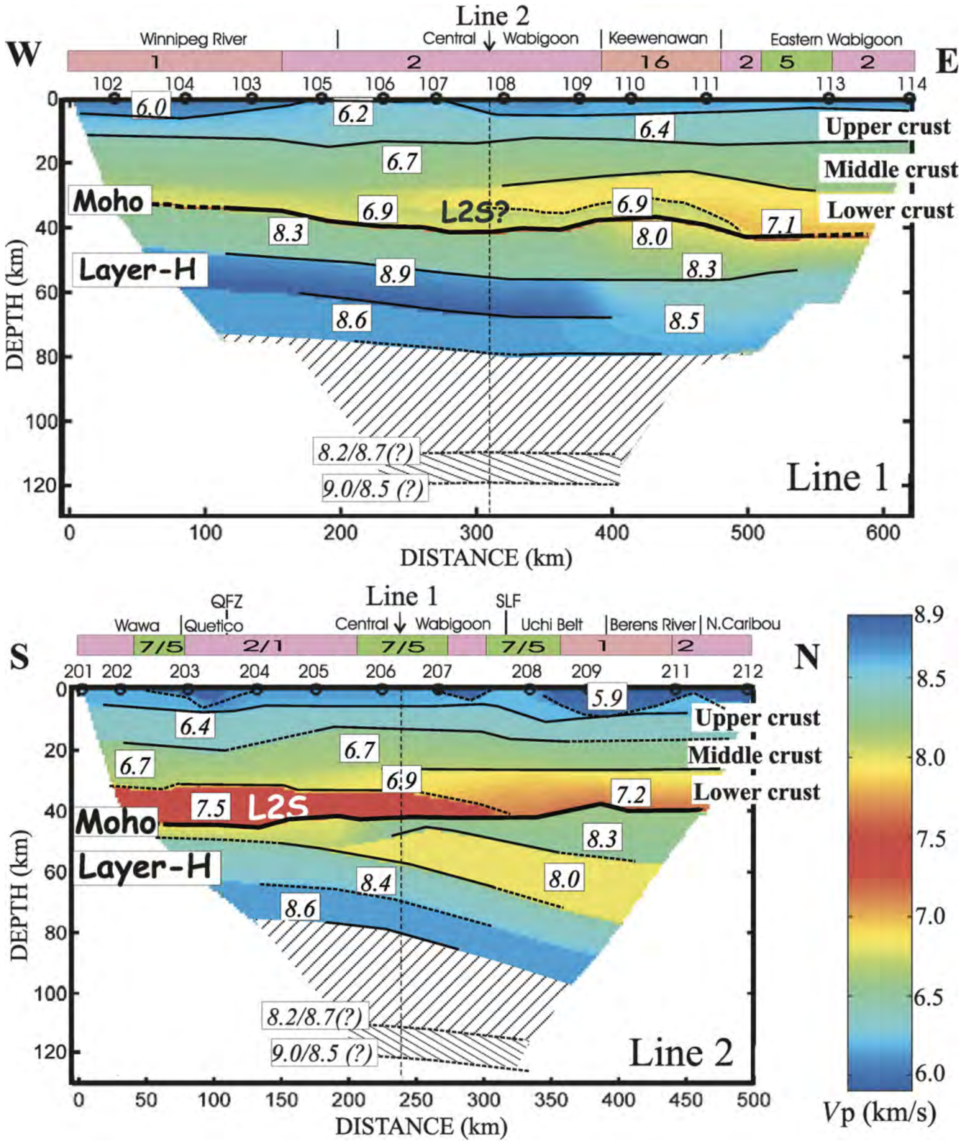
Alberta basement and SNORCLE

The Alberta basement study (Fig. 21) consisted of three separate seismic-reflection transects (Peace River Arch industry seismic experiment (PRAISE), the central Alberta transect (CAT), and the southern Alberta Lithoprobe transect (SALT)). Although each of these efforts had specific objectives, the overall purpose of the study was to establish the structure and tectonic evolution of the Canadian Shield Precambrian basement beneath the Phanerozoic strata of the Western Canada Sedimentary Basin (WCSB; Ross 2002).

Within Alberta, northeastern British Columbia, and the southern Northwest Territories, the Moho deepens westward and southward (Figs. 2, 3). Beneath the Archean portions of the Canadian Shield (e.g., Ray – Hearne Province in northeastern Alberta), the Moho is typically at a depth of ~35 km (Figs. 2, 3). In the northern part of the map area (Northwest Territories), the depth to Moho varies little from the Slave Province (~35 km), across the Wopmay Orogen and to the eastern front of the Cordillera. In the central part of the map area (northern Alberta and northeastern British Columbia), the Moho deepens slightly (by ~2–3 km) beneath the Peace River Arch area but remains between 35 and 38 km to the Cordillera deformation front (Figs. 2, 3) and appears to remain at about this depth into the Cordillera past the Rocky Mountain Trench (Mair and Lyons 1976). In southern Alberta, the Moho deepens substantially to ~45 km east of the Cordillera in the southeastern Alberta (Figs. 2, 3) and continues to deepen southward into the Wyoming Province of the United States. This southward crustal thickening coincides with an increase in the thickness of a layer of high-velocity (V_p ~ 7.5 km/s) lower crust (Clowes et al. 2002; Gorman et al. 2002).

When combined with seismic data from the Northwest Territories (Figs. 1–3), the results from Alberta and northeastern British Columbia appear to display a consistently deeper Moho south of the GSLSZ when compared with re-

Fig. 16*a*. Interpretation of the two crossing seismic-refraction profiles as illustrated in Musacchio et al. (2004). Note the high-velocity lower crust in the southern part of line 1 (L2s) and the dipping zones within the mantle north of there. These characteristics have been interpreted to be associated with subducted oceanic crust (Musacchio et al. 2004).



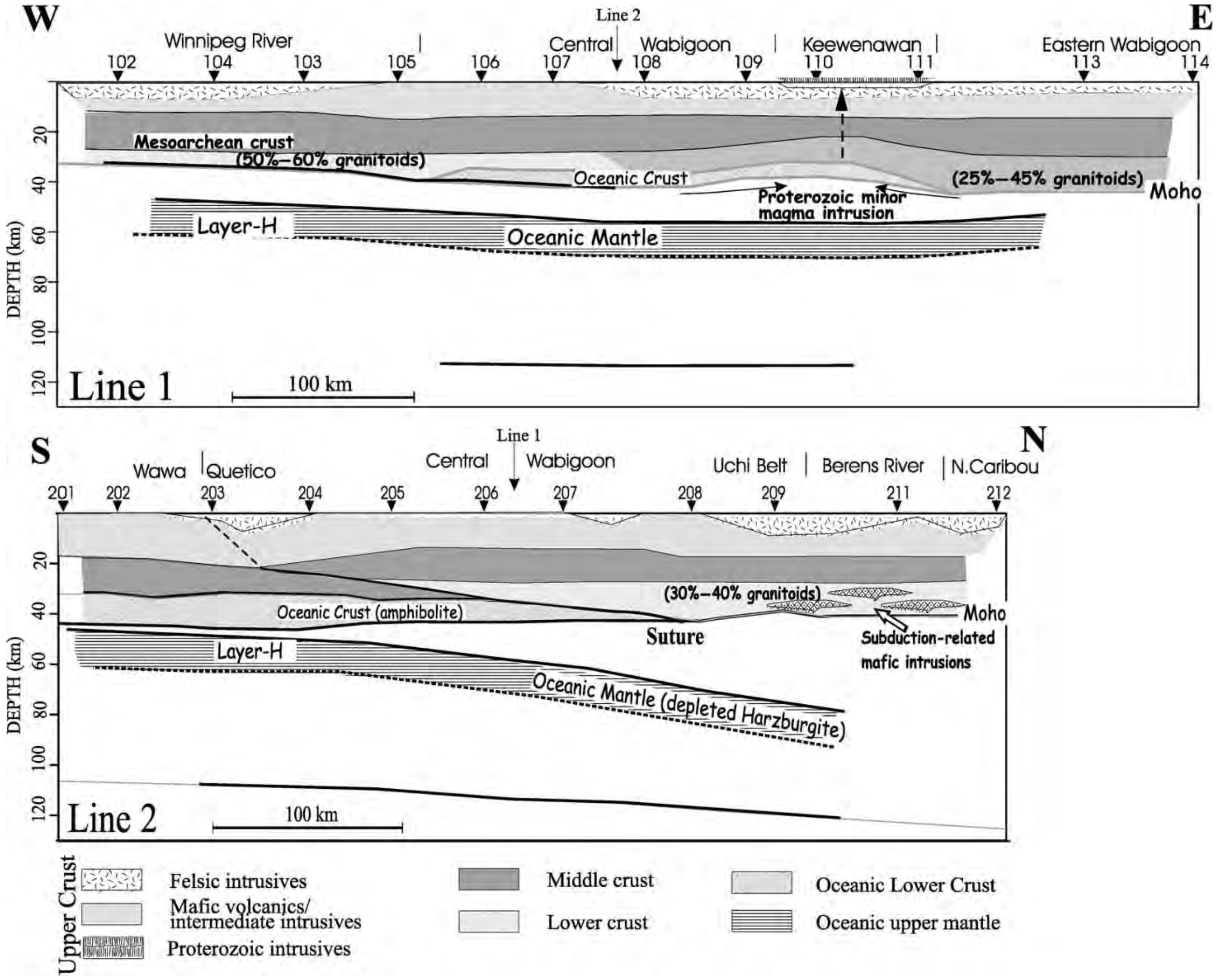
sults from north of the shear zone. Whether this transition occurs at the GSLSZ or whether it is more gradual is not known due to the sparse data. However, results from a teleseismic study do not appear to indicate a substantial offset of the Moho at the GSLSZ (Eaton and Hope 2003).

Most of the westward deepening of the Moho beneath the southern Cordillera may be an isostatic response to loading of the lithosphere by thrust sheets during Mesozoic – early Tertiary contraction (e.g., Price 1981; Cook 1995) and as expressed in regional gravity data (Eaton et al. 2000). Indeed, the reflection Moho is observed to be essentially parallel with the westward deepening of the top of the Precambrian shield beneath the WCSB in southern Alberta (Cook et al. in press). This implies that the age of the Moho must be greater than that of the load that caused deflection of the basement.

Local variations in Moho depth occur beneath the WCSB (Fig. 22). Notable among these are a local shallowing; or high (~2 km) beneath the Peace River Arch, a deepening; or low (~6–8 km) near Edmonton and a low of ~4–5 km in the Vulcan area southwest of Calgary (Vulcan low; Eaton et al. 1999, 2000). The causes of these perturbations are different for each. The Moho rise beneath the Peace River region is attributed to Paleoproterozoic crustal extension (Bouzidi et al. 2002), whereas the Edmonton low is attributed to a crustal penetrating fault. The Vulcan low has been interpreted different ways, including a Precambrian rift (Kanasewich et al. 1969) and, more recently, as a ~1.8 Ga collisional belt at the northern margin of the Wyoming Province (Eaton et al. 1999).

In southernmost Alberta, the crust deepens continuously from ~45 km at Edmonton to ~56–58 km at the United States – Canada border (Figs. 2, 3, 23). The deep Moho continues southward into Montana and spatially correlates with the Archean Medicine Hat block in Canada and the Archean Wyoming Province in Montana (Clowes et al. 2002). In addi-

Fig. 16*b*. (*concluded*). Interpretation of seismic-refraction profiles in the Western Superior transect illustrating an interpreted amphibolitic layer in the lower crust that may have originated as oceanic crust (Musacchio et al. 2004).



tion, the crustal thickening is associated with a high-velocity (>7.5 km/s) layer that may be as much as 20 km thick in Montana (Fig. 23*b*). Although the deep Moho and high-velocity lower crust coincide with Archean rocks near the surface, Paleoproterozoic (ca. 1.74–1.82 Ga; Davis et al. 1995) ages of lower crustal xenoliths from within the high-velocity layer have led to interpretations that rely on Paleoproterozoic magmatic and (or) structural underplating (Lemieux et al. 2000; Clowes et al. 2002).

The Cordillera (SNORCLE and Southern Cordillera transects)

In the Cordillera of western Canada (Fig. 21), the geophysical Moho displays both rapid and undulatory changes in depth. In the southeastern Cordillera, beneath the Foreland thrust and fold belt, the Moho deepens to ~50 km from ~40 km beneath the WCSB (Figs. 2, 22). According to interpretations of both seismic-reflection (e.g., Cook 1995) and seismic-refraction profiles (Clowes et al. 1995), the Moho then undergoes a rapid westward decrease in depth to ~35 km (Figs. 2, 3). Whether this change is very nearly a step or whether it occurs as a relatively steep ramp is uncertain.

The age of the Moho in the southern Cordillera is somewhat uncertain. As noted previously, beneath the WCSB and Foreland belt, the Moho is parallel to the top of the basement. As the basement was deflected beneath the load of the thrust sheets (Cook et al. in press), the age of the Moho there must predate the thrust emplacement (Mesozoic). West of there, however, where the depth to Moho decreases, there are two likely interpretations for the age of the Moho. In the first interpretation, it is older than the contraction and may be as old as Mesoproterozoic (Cook 1995). Indeed, radiometric dates of upper mantle xenoliths throughout the Cordillera provide evidence that the mantle is Precambrian (Armstrong et al. 1991; Peslier et al. 2000). A second interpretation is that the Moho is young and that the westward decrease in depth to the Moho is associated with postorogenic extension (Cook et al. 1988; Cook 1995; Monger and Price 2003). In this model, the crust may have been substantially thicker during contraction but then thinned as a result of lithospheric uplift and stretching.

In the northern Cordillera, the Moho displays a similar westward decrease in depth (Fig. 24) to that observed beneath the southern Rocky Mountain trench. In the north, however, the change occurs beneath the WCSB east of the

Fig. 17. Foldout 2. Seismic-reflection data along the north–south corridor in the Western Superior transect (modified from White et al. 2003; Van der Velden 2007). Note that the lower crust on the south is reflective and corresponds to the high-velocity layer observed in the refraction data and that reflections are observed dipping northward from the lower crust into the upper mantle.

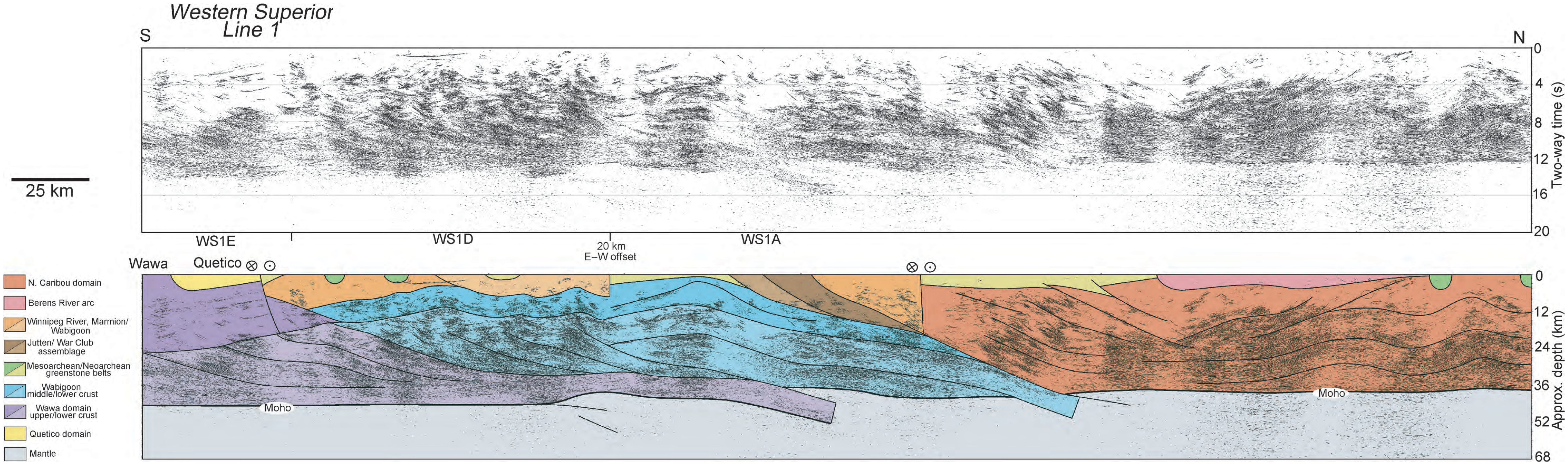


Fig. 18. Map of the Trans-Hudson Orogen transect region showing the locations of the seismic-refraction (black) and seismic-reflection (red) profiles (Németh et al. 2005). SBZ, Superior Boundary Zone.

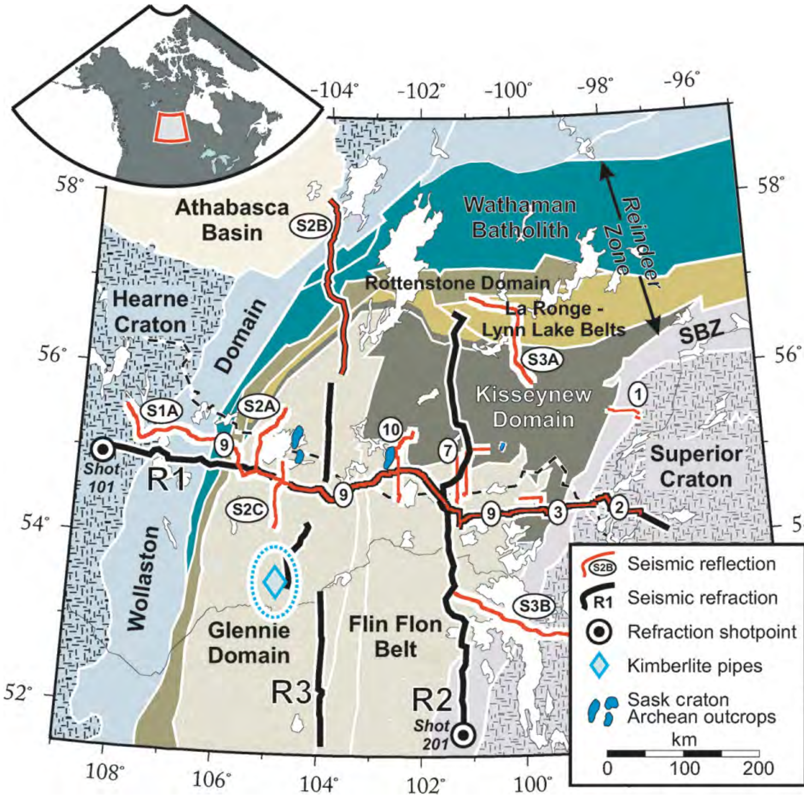
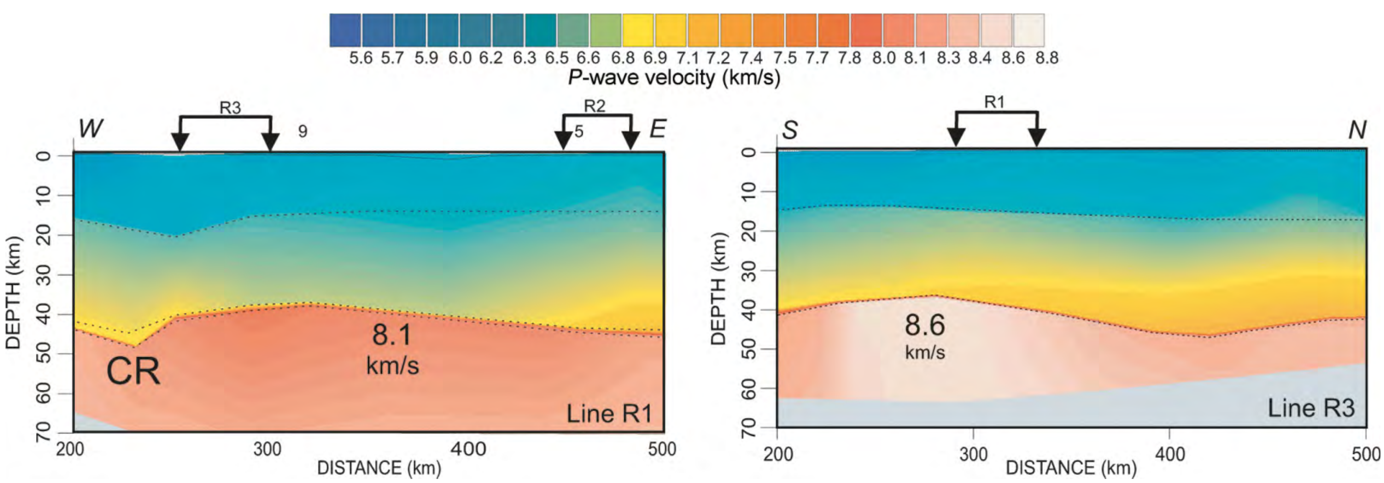


Fig. 19. Interpretation of the central segments of seismic-refraction profiles R1 (east–west) and R3 (north–south) in the Trans-Hudson Orogen transect (modified from Németh et al. 2005). See Fig. 18 for locations. Note the differing upper mantle velocities in R1 and R3. CR, crustal root.

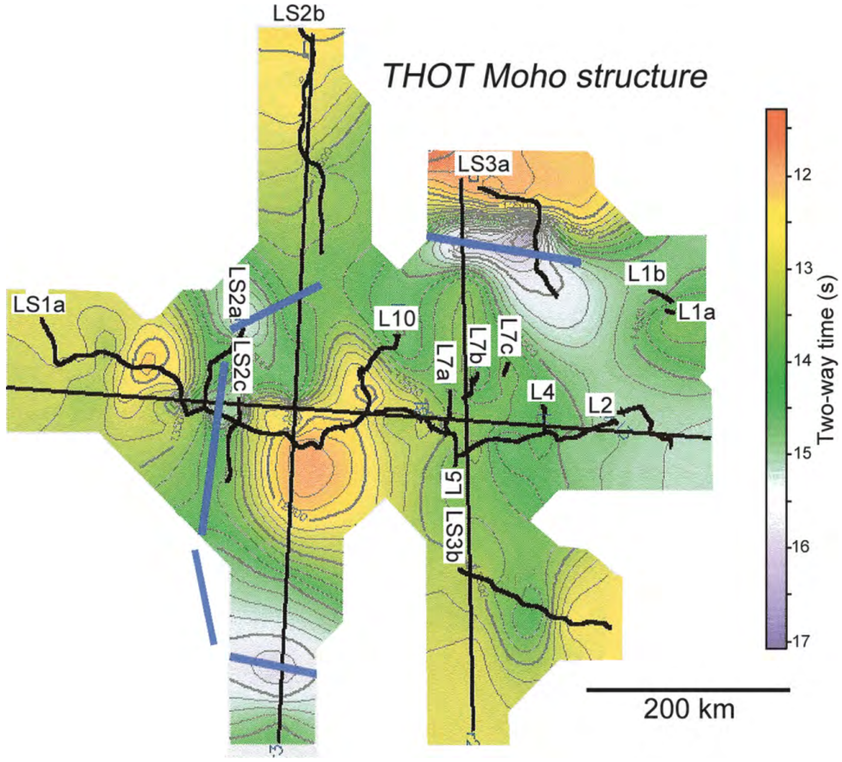


Cordillera. Although it is uncertain whether this change is correlative with the one in the southern Cordillera, it is likely that it is Precambrian because it occurs beneath westward thickening Precambrian strata (Cook et al. 1999; Welford et al. 2001).

The Moho in the central and western Cordillera, at least to the Coast Mountains, is somewhat undulatory with no observable rapid changes in depth. The depth varies between 30 and ~35 km (Fig. 24) and the undulations commonly exhibit half wavelengths of 50 km or more (Fig. 24). In combination with SNORCLE profiles east of the Cordillera, the Moho is relatively shallow (30–35 km) from the Slave Province to the western Cordillera (Figs. 2, 3). Thus, from the Archean (~2.6 Ga) Slave Province to beneath the Paleoproterozoic (~1.85 Ga) Wopmay Orogen and then across the Cordillera, there is little change in travel time to the reflection Moho or in depth to the refraction Moho, with the exception of the transition beneath the Proterozoic Fort Simpson basin.

At the western margin of the Cordillera, Moho depth appears to change beneath the Coast Mountains (Clowes et al. 1995; Hammer et al. 2000; Clowes et al. 2005). On the west

Fig. 20. Map of two-way reflection travel times in the Trans-Hudson Orogen Transect (THOT; line locations in black and labeled illustrating the deep regions (thick purple lines) that are interpreted as a crustal root associated with the Sask craton (modified from Clowes et al. 2010).



coast in the northern Cordillera, the Moho shallows toward the Pacific Ocean (Hammer et al. 2000; Morozov et al. 2001). In the northern Cordillera, the crust may thin by as much as 10 km from the intermontane region to the Coast Mountains and thin further into the Pacific Ocean (Hammer et al. 2000; Fig. 24). Thinned crust beneath the Coast Mountains in this area has been interpreted to result from postaccretion extension (Hammer et al. 2000).

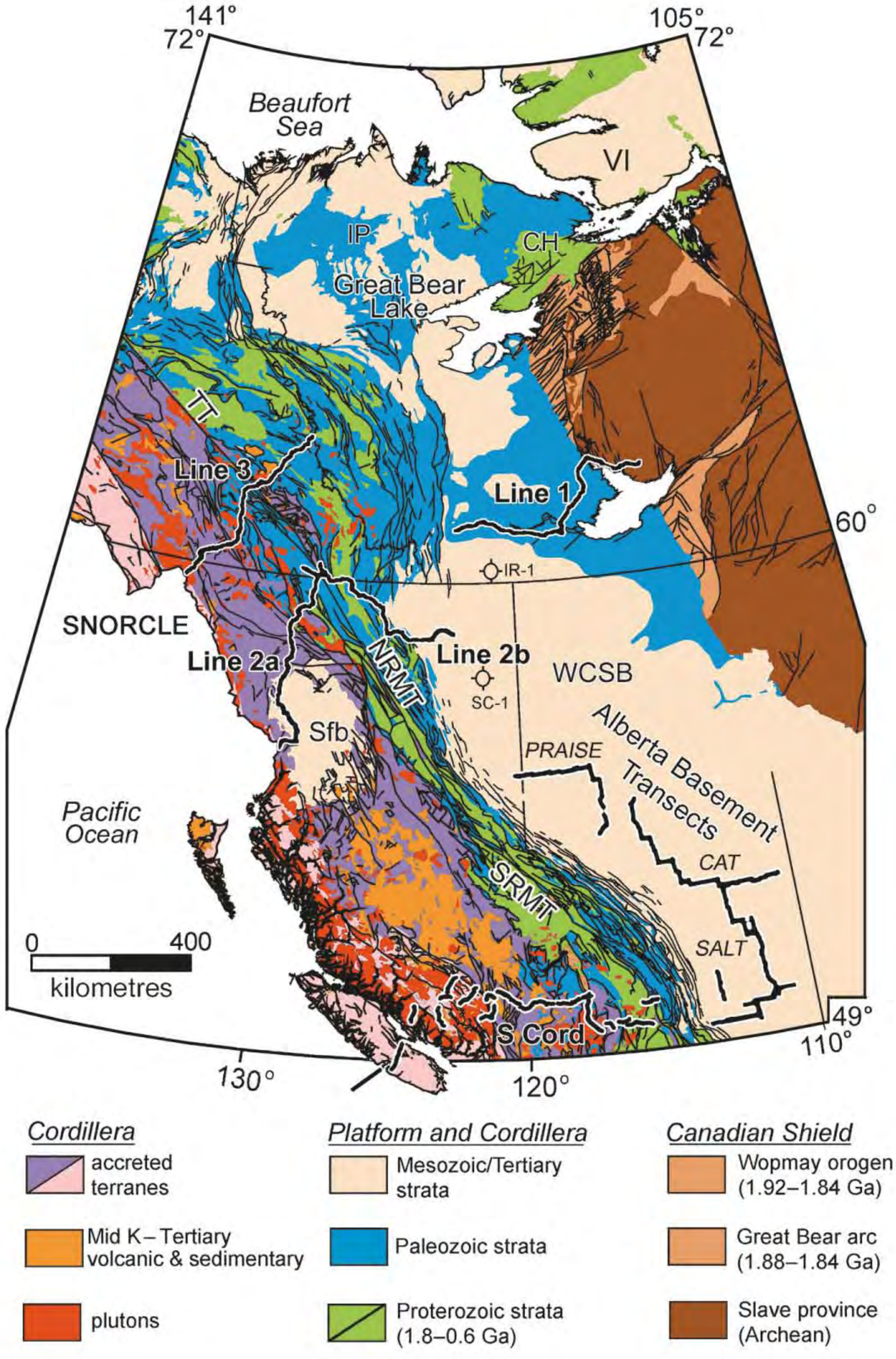
In the southern Cordillera, the crust appears to thicken by a few kilometres beneath the Coast Mountains relative to the Intermontane region and then thins toward the plate edge (Zelt et al. 1992; Varsek et al. 1993; Clowes et al. 1995). Across Vancouver Island and in the western Coast Mountains, the crust appears to consist of subcreted material (Clowes et al. 1987), making the identification of a single Moho difficult. In the near offshore Vancouver Island, both the top and bottom of the Juan de Fuca plate are imaged (Clowes et al. 1987). Reflections from the downgoing plate are scarce; however, its position is constrained by refraction data and potential field studies (Clowes et al. 1995). Nevertheless, the position of the downgoing slab as just described is questioned by results from recent natural source seismic studies. Based on converted phases and inferred anisotropy from a series of closely spaced teleseismic stations across the subduction zone, Nicholson et al. (2005) interpreted the top of the Juan de Fuca plate to be $\sim$10 km shallower than that from active-source seismic data. If correct, this further complicates the existence of a continental Moho in the region. At present, the different interpretations cannot be reconciled.

Detailed structures near the Moho

Detailed structures in the vicinity of the geophysical Moho are delineated primarily from seismic-reflection data, as these data provide the highest resolution. To describe these structures, the approximate position of the refraction Moho on the reflection profiles is determined by converting the Moho depth to approximate reflection travel time. Because refraction measurements are made with head waves that are typically lower frequencies than reflection signals and because refraction profiles are commonly not recorded at the identical locations as reflection profiles, it is difficult to match detailed waveforms from reflection profiles to waveforms from refraction profiles. Nevertheless, the conversion of refraction depth to reflection travel time is sufficiently accurate to analyze the geometry of reflectors near the Moho.

In addition to regional variations of the reflection Moho that are similar to those observed along refraction profiles, although with greater detail on some of the transitions, reflection profiles exhibit a number of different near-vertical incidence reflection characteristics near the Moho. Different schemes have been proposed to categorize the reflection patterns near the Moho (Hammer and Clowes 1997; Cook 2002) but all appear to partition into three major categories: (1) no clear reflections in the vicinity of the Moho (Fig. 25*a*), including either no reflections at all or a downward fading of reflectivity; (2) a variety of structures that are underlain by a subhorizontal distinct reflection that delineates the base of reflectivity (Figs. 25*b*, 25*c*); and, in a few cases, (3) reflections that project below the Moho into

Fig. 21. Map of western Canada showing the Alberta Basement, Southern Cordillera (S. Cord), and SNORCLE transect regions (modified from Cook et al. 2005). Black lines show the locations of regional seismic-reflection profiles. In the Alberta Basement Transects, PRAISE is the Peace River Arch Industry Seismic Experiment, CAT is the central Alberta transect, and SALT is the Southern Alberta Lithosphere Transect. CH, Coppermine homocline; IP, Interior platform; Sfb, Skeena fold belt; TT, Tintina fault.

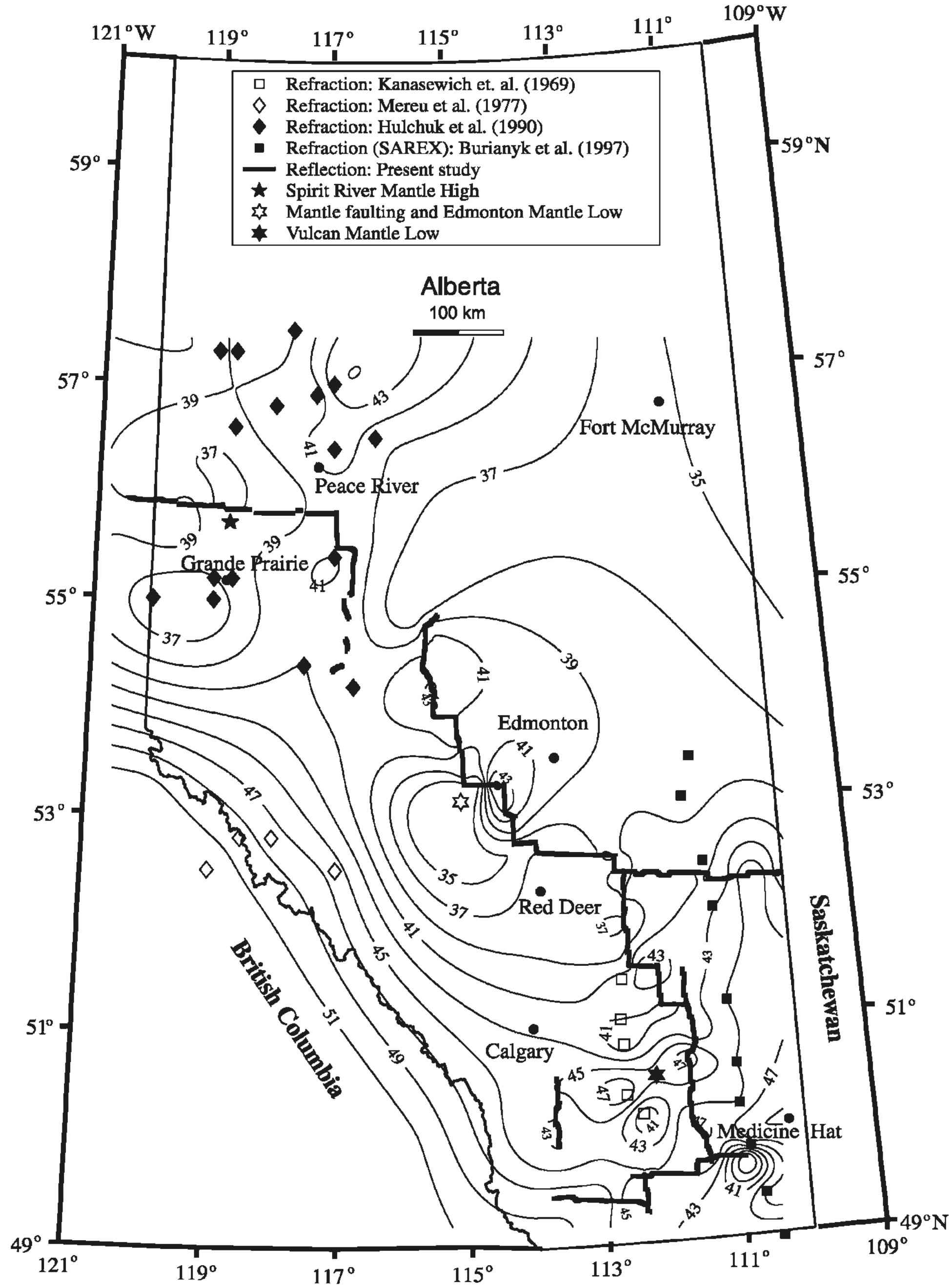


the upper mantle (Figs. 25*c*, 25*d*). Examples of these are illustrated in following sectionss.

No clear reflection boundary

In some areas, there are no clear reflection(s) from the crust–mantle transition, although there may be a diffuse transition from reflective crust to transparent mantle. If diffuse arrivals are visible, the reflection Moho is delineated as the base of reflectivity. If the lower crust and upper mantle are both nonreflective, however, no reflection Moho can be defined. In these cases, converting the crustal depths from regional refraction profiles to reflection travel time can approximate the position of the crust–mantle transition. An example of complete lack of reflections (type Ia of Cook 2002) is visible in the Fort Simpson region along SNORCLE line 1 (Fig. 25*a*). Examples of fading of crustal reflectivity

Fig. 22. Map of the Alberta Basement transect region with contours of depth to Moho (modified from Bouzidi et al. 2002). The estimates of Moho depth are from a number of seismic-refraction studies and from depth-migrated seismic-reflection data. SAREX, Southern Alberta Refraction Experiment.



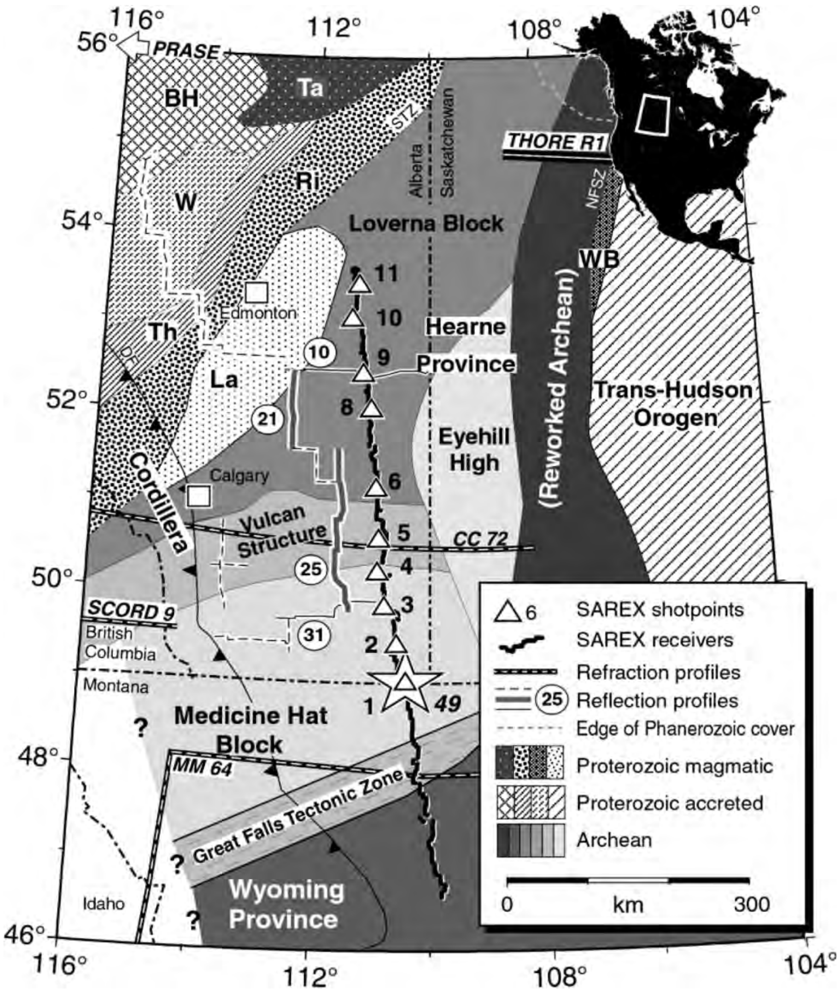
(class 3 of Hammer and Clowes 1997; type Ib of Cook 2002) are visible along Trans-Hudson Orogen line 9 (Cook 2002).

Distinct (subhorizontal) reflection(s) at base of crustal reflectivity

In many areas, the reflection character at appropriate travel times includes one or more subhorizontal reflections that may be continuous over long distances and that may even be present beneath regions with different ages of surface rocks. A number of different geometrical relationships have been identified between these subhorizontal reflections and the crustal reflectivity above. Perhaps the simplest structures are layers in the lower crust that are parallel to the reflection Moho (classes 1 and 2 of Hammer and Clowes 1997; type Ia of Cook 2002) as observed in Ft. Simpson area along SNORCLE line1 (Fig. 25*b*) and along line 11 in the Southern Cordillera (fig. 4*b* in Cook 2002).

As resolution of reflection data has improved with time, the nature of the junction between dipping lower crustal reflections and the subhorizontal reflection Moho has been observed. In some areas, layers in the lower crust are geometrically discordant with the subhorizontal reflection Moho and appear to be truncated at the Moho (type IIb of Cook 2002). Examples of this geometry are visible in the

Fig. 23*a*. Map of the Alberta Basement transect region with the location of the Southern Alberta Refraction Experiment (SAREX) indicated (modified from Clowes et al. 2002). Precambrian domains below the Western Canada Sedimentary Basin are BH, Buffalo Head; La, Lacombe; Ri, Rimbey; SCORD, Southern Cordillera transects; Ta, Taltson; Th, Thorsby; THORE, Trans-Hudson Orogen Refraction Experiment; W, Wabamun; WB, Wathaman batholith.



western Slave Province along SNORCLE line 1. In other areas, however, layers in the lower crust appear to be listric into the reflection Moho as observed along line 10 in the Southern Cordillera (e.g., fig. 6*b* of Cook 2002).

Reflections projecting from the lower crust into the mantle beneath reflection Moho

Improvements of data quality, both in acquisition and processing, over the length of Lithoprobe have provided increasing numbers of observations of reflections projecting from the lower crust to beneath the reflection Moho (Cook 2002). In some cases, the dipping reflections appear as simple, single reflections, as in the Abitibi–Opatica dataset (Fig. 13); whereas in others, they are multilayered, as along SNORCLE profile 1 (Fig. 25*a*). In a few examples, the crustal reflections appear to project through a subhorizontal reflection Moho, as in central Alberta (Fig. 25*d*).

When reflections cross a subhorizontal reflection Moho, the possibility of three-dimensional effects (e.g., sideswipe) have to be considered. However, in cases where three-dimensional effects have been quantified, for example by crooked line geometry or crossing lines, results provide evidence that the crossing geometry is real (e.g., Van der Velden and Cook 2005).

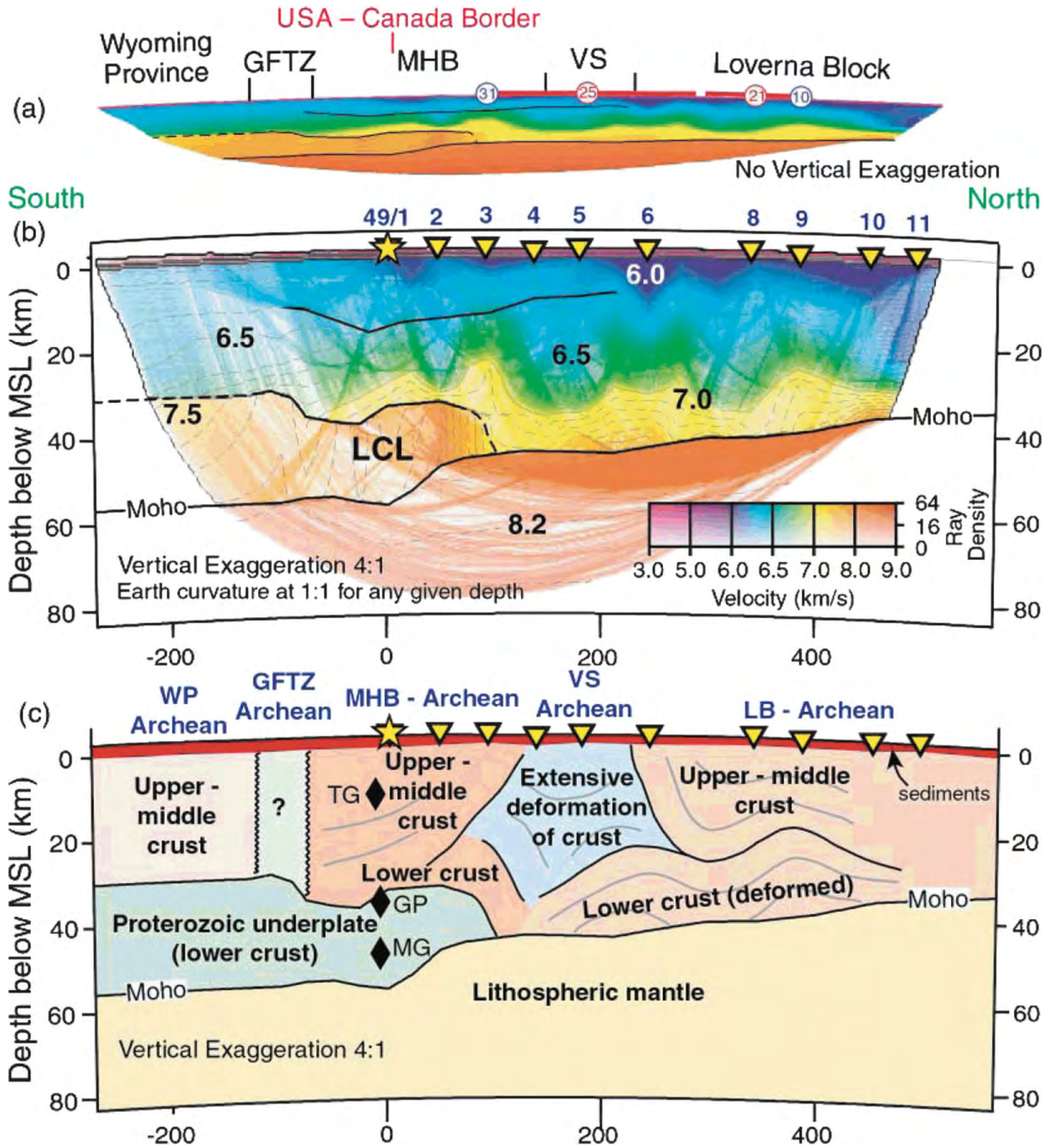
Discussion

Age of the Moho

The age, or relative age, of the Moho is determined only indirectly, and even then only approximately, by (1) correlating with ages of surface rocks, (2) correlating with ages of xenoliths, and (3) mapping geometric relationships with layers whose age can be approximately determined. Correlating with ages of surface rocks has proven to be highly inaccurate because processes that postdate the formation of the Moho may serve to alter its structure, depth, and physical properties. Such processes could include thermal (e.g., magmatic underplating or intrusion, partial melting and restite formation), structural (e.g., structural underplating, tectonic wedging, subcretion), or a combination (e.g., delamination and associated asthenospheric upwelling).

Correlating the approximate age of the Moho with lower crustal xenoliths is possible in those few areas where such xenoliths are present (Moser and Heaman 1997; Davis et al.

Fig. 23*b*. (*concluded*). Interpretation of the SAREX profile illustrating a lower crustal layer (LCL) that has very high *P*-wave velocity (>7.5 km/s). Xenoliths derived from LCL indicate that it is a Paleoproterozoic mafic granulite that is younger than the Archean rocks near the surface (Davis et al. 1995). Layer LCL is thus interpreted as an underplate, either magmatic or structural. Note that the Earth's curvature is incorporated. GFTZ, Great Falls tectonic zone; LB, Loverna Block; MHB, Medicine Hat Block; VS, Vulcan Structure; WP, Wyoming Province. Black diamonds are approximate source depths for xenoliths: GP, garnet paragneiss; MG, mafic gneiss; TG, tonalitic gneiss. For locations, see Fig. 23*a*.



1995). In the Abitibi portion of the Superior Province, overgrowths on deep crustal zircons indicate reworking $\sim$350 Ma later than the formation of the core of the zircon (Moser and Heaman 1997). In southern Alberta, for example, ages of crustal xenoliths decrease downward from $\sim$2.6 Ga from the upper crust ($\sim$5–15 km) to $\sim$1.85 equal to 1.75 Ga at depths of $\sim$37–40 km (pressure 1.24 GPa) and then to $\sim$1.75–1.7 Ga at $\sim$41–44 km (1.35 GPa; Davis et al. 1995). In this case, the age of the Moho is likely related to either structural or underplating processes (Lemieux et al. 2000; Clowes et al. 2002).

In other areas, ages of xenoliths from the upper mantle place additional limits on the age of the Moho. This is perhaps most pronounced and problematic in the Cordillera where virtually all radiometric ages of mantle xenoliths are Proterozoic. In southern British Columbia, Rb/Sr measurements provide ages that are typically $\sim$0.7–1.2 Ga (Armstrong et al. 1991), whereas Os measurements provide ages of $\sim$1.5 Ga from elsewhere (Peslier et al. 2000). Although tectonism, including lithospheric accretion, contraction, and subsequent extension, took place during the late Paleozoic – Tertiary, there appears to be little or no evidence of substantial modification of the upper mantle ages during these episodes (Cook et al. in press).

Regional geometric variations may assist in constraining the age of the Moho. For example, in the southern Canadian Cordillera, the surface of the autochthonous basement in the foreland is deflected due to the loading of the overlying stacked thrust sheets. The Moho is parallel to this surface and was thus deflected as well (Cook et al. in press). Accordingly, the age of the Moho beneath the foreland must exceed the age

Fig. 24. Foldout 3. Seismic refraction cross sections of the northern (top) and southern Cordillera (modified from Clowes et al. 1995; Hammer et al. 2000). The profiles have been lined up along a crustal-scale ramp and westward shallowing of the Moho (near the Rocky Mountain trench in the south, the Fort Simpson basin east of the Cordillera in the north; Cook et al. 2005). Numbers are velocities in km/s. SCORE, Southern Cordillera Refraction Experiment; SNORE, Slave – Northern Cordillera Refraction Experiment; SCCT, Southern Canadian Cordillera Transect; VISP, Vancouver Island Seismic Program.

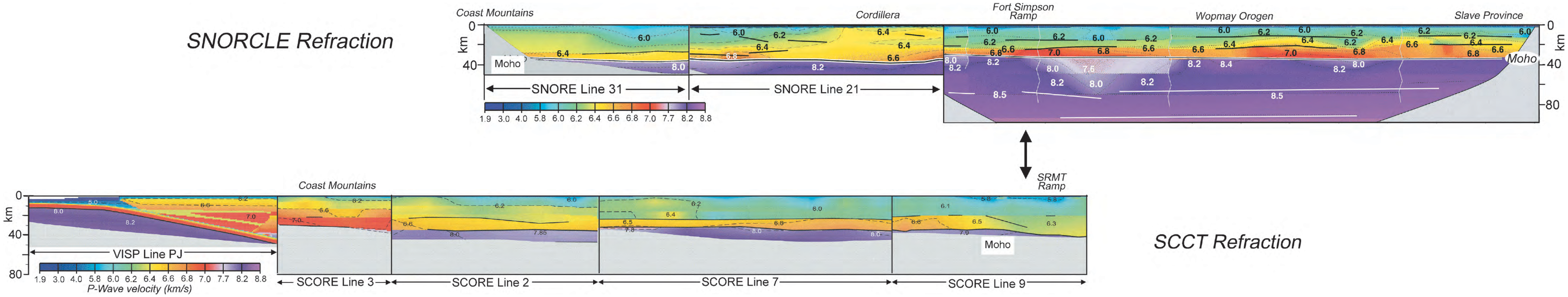
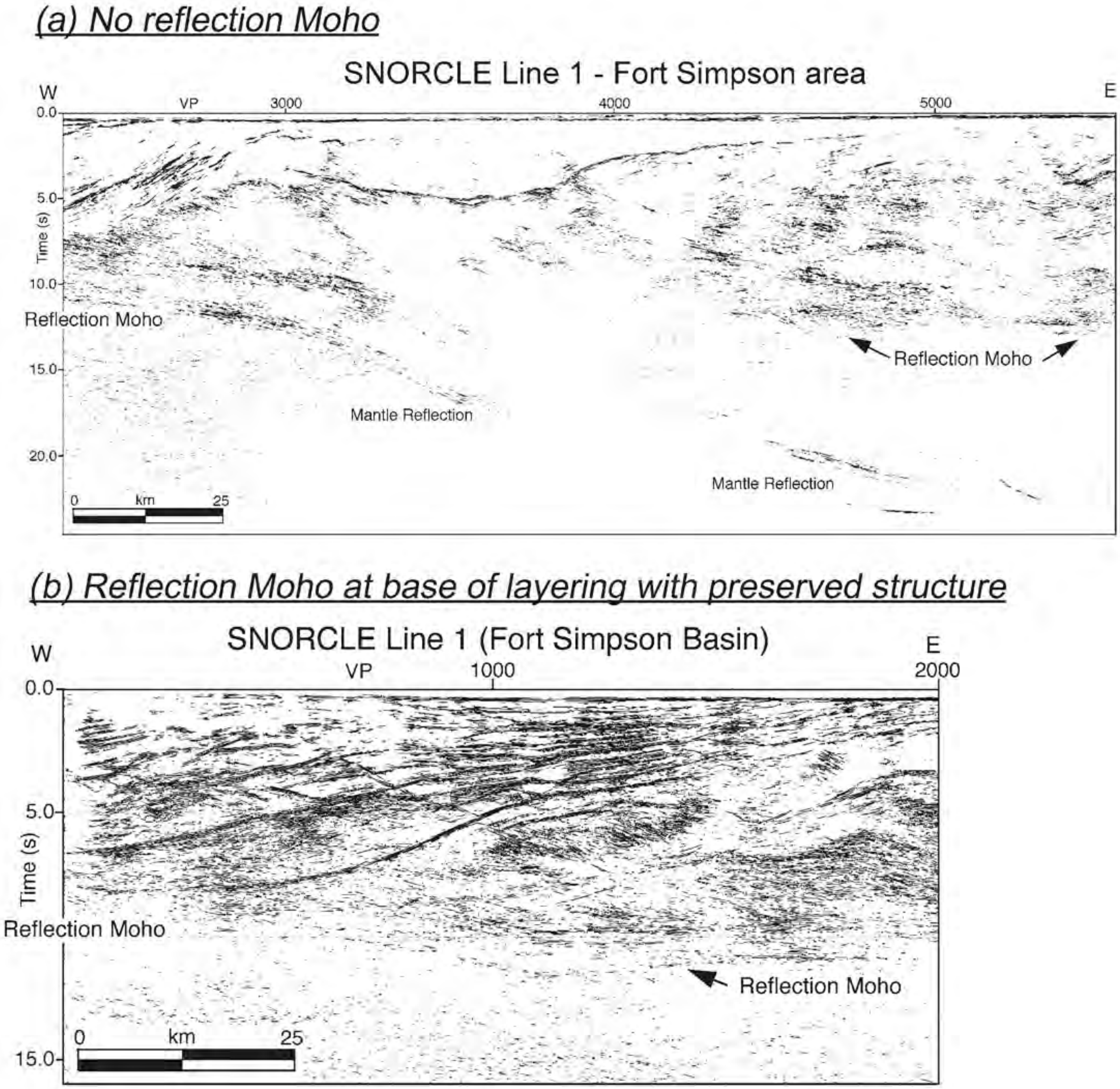


Fig. 25. Examples of different reflection characteristics in the vicinity of the Moho. (*a*) No reflections from the vicinity of the Moho in the Fort Simpson area of the SNORCLE transect (Cook et al. 1999). Here the lack of reflections is not due to lack of signal as reflections are visible from longer travel times. One interpretation is that dewatering of a subducted lithosphere produced serpentinization, reduction in the seismic velocities and thus reduction in the contrasts at the Moho (Cook et al. 1999; Fernandez-Viejo et al. 1999; Eaton 2006). VP, vibrator point. (*b*) Distinct reflection Moho at the base of crustal layering and preservation of structure along the Moho in the Fort Simpson region of the SNORCLE transect (Cook et al. 1999).



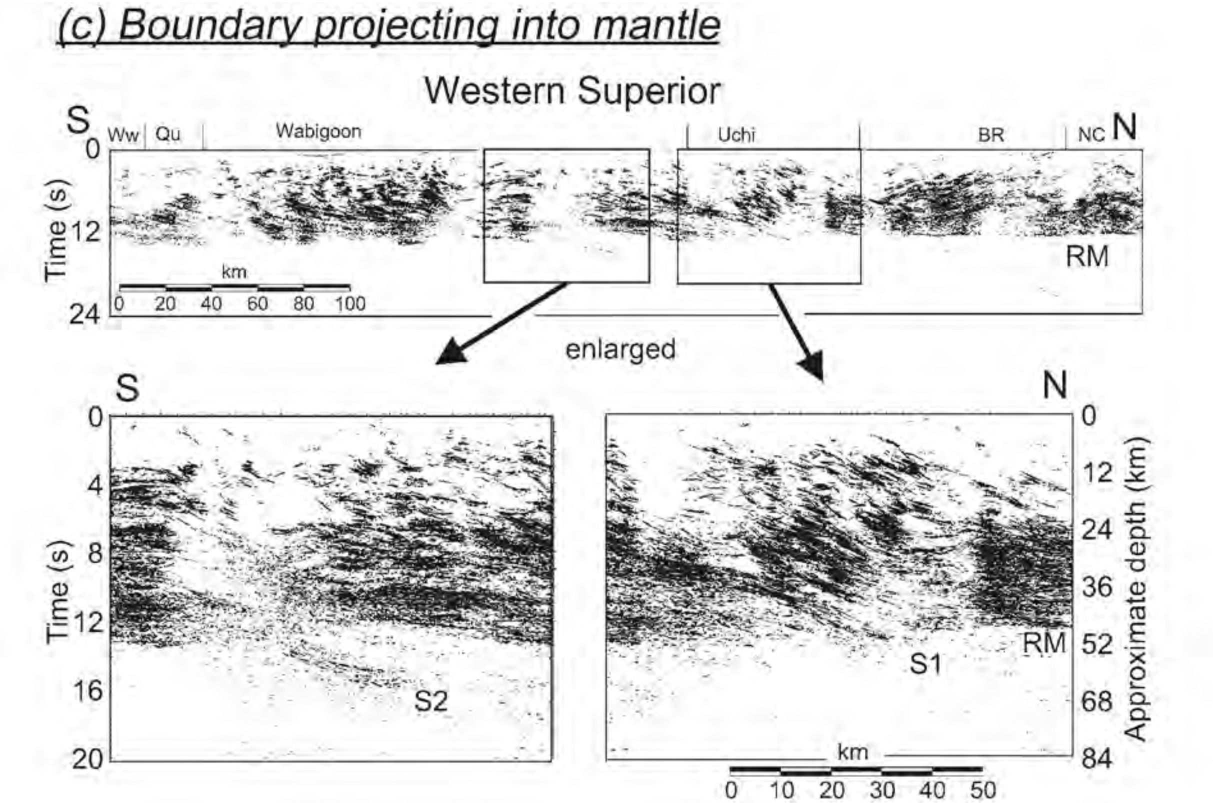
of the thrusting in this part of the orogen — Late Cretaceous to early Tertiary.

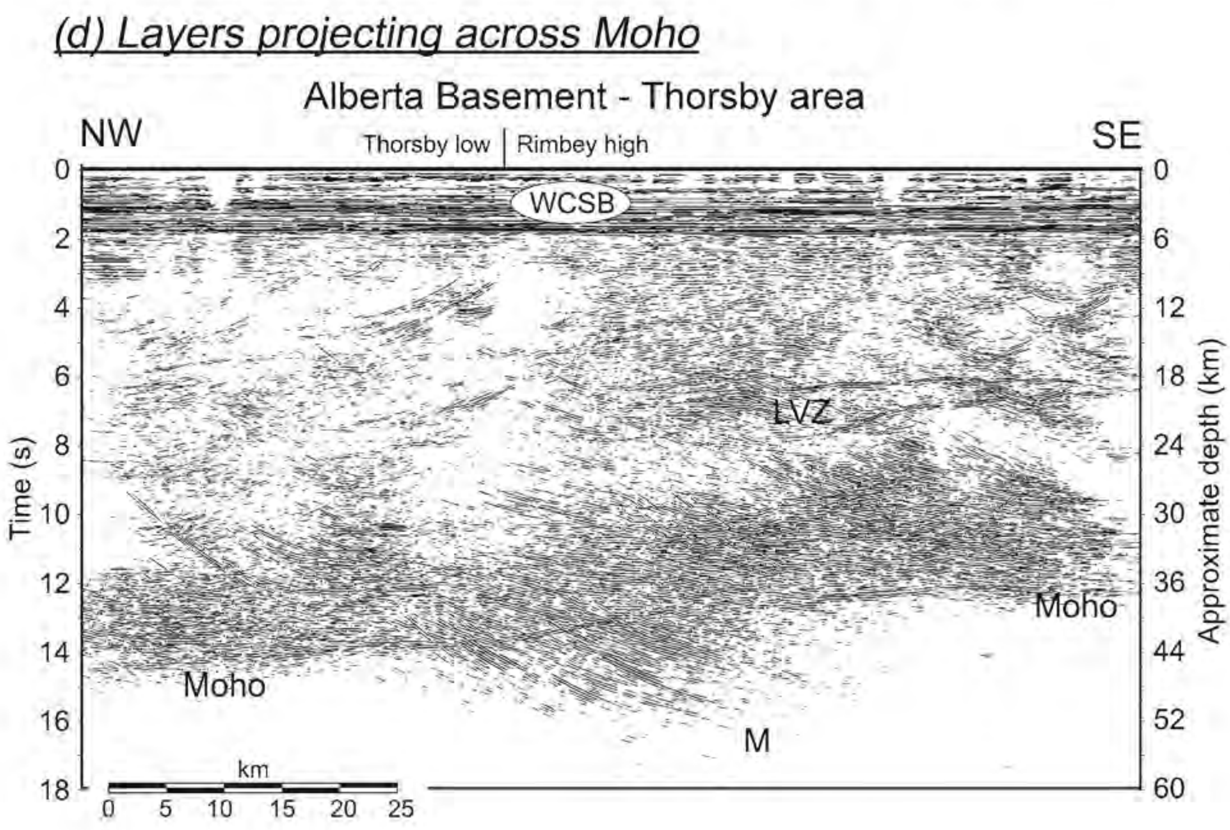
Detailed geometric relationship between the reflection Moho and adjacent features provides evidence for relative ages; the reflection Moho must be younger than layers it crosses and is likely older than or coeval with layers that flatten into it. Examples of both are found most of the Lithoprobe transects but are particularly clear, as data quality of some of the more recent profiles has improved (e.g., Cook 2002; Van der Velden et al. 2004).

Multiple origins for the continental Moho

The origins of the continental Moho and crust–mantle transition are probably as varied and complex as the origin and development of continental crust. It is important to recognize that images, whether seismic or other, obtained today repre-

Fig. 25 (*concluded*). (*c*) Reflection boundaries projecting from the lower crust into the upper mantle in the western Superior transect (White et al. 2003; Van der Velden and Cook 2005). BR, Berens River terrane; NC, North Caribou terrane; Qu, Quetico terrane; RM, reflection Moho; S1 and S2, reflections projecting beneath Moho; Ww, Wawa terrane. (*d*) Reflections projecting into the upper mantle across a sub-horizontal reflection that can be linked to the refraction Moho (Van der Velden and Cook 2005). This example is from the Thorsby area (Th in Fig. 23*a*) of the central Alberta transect. LVZ, low-velocity zone; M, mantle reflection; WCSB, Western Canada Sedimentary Basin.





sent a "snapshot" in time. The crust and Moho have, in some cases, been subjected to extensive periods of tectonism, alteration, and possible resetting that resulted in the product we see today. Following are some origins that have been proposed.

Old oceanic Moho

In some regions, structural emplacement of oceanic rocks beneath older continental or arc crust may account for younger rocks at depth (Davis et al. 1995), as well as lower crustal rocks with high velocities (Eaton et al. 2000; Clowes et al. 2002). If this occurs, either (1) the crust–mantle transition of the old oceanic crust could remain as part of the lower continental crust and the subducted oceanic Moho could subsequently be identified as the continental Moho (Fig. 26*a*) as in the Lithoprobe East (Van der Velden et al. 2004), the Abitibi–Opatica (Fig. 13), the Western Superior (Fig. 16), and the SNORCLE (Cook et al. 1999) transects; or (2) the subducted basaltic oceanic crust could undergo a phase change to eclogite, thus producing a new Moho (refraction Moho and perhaps also reflection Moho) above the eclogite. In this case, more felsic rocks above would be lower density and relatively weak, whereas the eclogite below would have geophysical characteristics that are appropriate for upper mantle (Fig. 26*a*) and could be relatively strong (Cook 2002).

Thermal front (e.g., partial melting and removal of light fraction)

Partial melting and fractionation of either intermediate composition rocks (granodioritic–andesitic igneous rocks) or pelitic metasedimentary rocks can modify the chemical and physical properties and reduce contrasts in material properties (e.g., Wyllie 1971; Hynes and Snyder 1995). In addition, such partial melting may produce mafic restites whose geophysical properties are appropriate for mafic lower crust or even upper mantle (Wyllie 1971; Vielzeuf and Holloway 1988; Hynes and Snyder 1995). Accordingly, elevated temperatures may produce partial melting that will preferentially remove lower density phases and leave residuals of fluid-absent, relatively homogenous (in terms of seismic properties), and high-density (high seismic velocity) mineral assemblages (e.g., Hynes and Snyder 1995; Rudnick and Fountain 1995; Cook 2002).

Some consequences of this process are that the reflection Moho could be "frozen" unless significantly higher temperatures occur and that the restite will have fewer and lower reflection contrasts, higher average seismic velocity, and higher average density than the material from which it was derived (Fig. 26*b*; Hynes and Snyder 1995; Cook 2002). Mafic granulites and garnet-bearing granulites often have velocities and densities that are similar to upper mantle values, even when corrected for elevated temperatures (up to 7.5–7.8 km/s or more at 6–10 kbar (Rudnick and Fountain 1995; Hynes and Snyder 1995)). This scenario has been proposed for parts of the Lithoprobe East (Van der Velden et al. 2004), SNORCLE (Cook 2002), and Alberta Basement (Cook 2002; Van der Velden and Cook 2005) transects.

Partial melting may not completely obliterate structural geometry near the reflection Moho because the restites may retain some of the structural fabric associated with their formation in the lower crust and because partial melting may not completely remove all of the lighter fraction. In other words, lower crustal rocks of some areas may become partially seismically homogenized, perhaps with velocities and densities near those of ultramafic rocks, but could retain an older fabric from the crust (e.g., Cook and Vasudevan 2003; Van der Velden et al. 2004; Fig. 26*b*). Furthermore, a thermally imposed compositional change from the more felsic crustal rocks above to the mafic restite below may become a prominent rheological contrast that could localize zones of detachment during subsequent deformation.

Magmatic underplating

In addition to structural emplacement of mafic and ultramafic rocks at depth, mafic igneous rocks may episodically intrude into the lower crust and upper mantle. As a result, they may spread laterally and ''underplate'' a region with relatively high-density and high-seismic-velocity material. They may intrude as sills into the lower crust, which could appear later as layered reflections (e.g., McKenzie 1984; Furlong and Fountain 1986). In this scenario, the Moho is located near the base of intrusive layers that may be younger than the overlying crust (Fig. 26*c*). Indeed, Nelson (1991) suggested that the lower crust nearly everywhere may be subjected to underplating, given sufficient time. A possible consequence of this process is that the transition from mafic igneous underplated material to ultramafic mantle rocks may develop as the basalt liquidus, in a similar manner to that of the ocean basins (e.g., Vogt et al. 1969). Magmatic underplating has been proposed in the Lithoprobe East transect (Hall et al. 1998), Eastern Canadian Shield Onshore–Offshore Transect (ECSOOT) (Hall et al. 2002), southern Alberta (Lemieux et al. 2000; Clowes et al. 2002), the Keeweenawan rift in Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) (e.g., Behrendt et al. 1988), and the central part of both the southern (Cook 1995; Hyndman and Lewis 1995) and northern (e.g., Hammer et al. 2000) Cordillera.

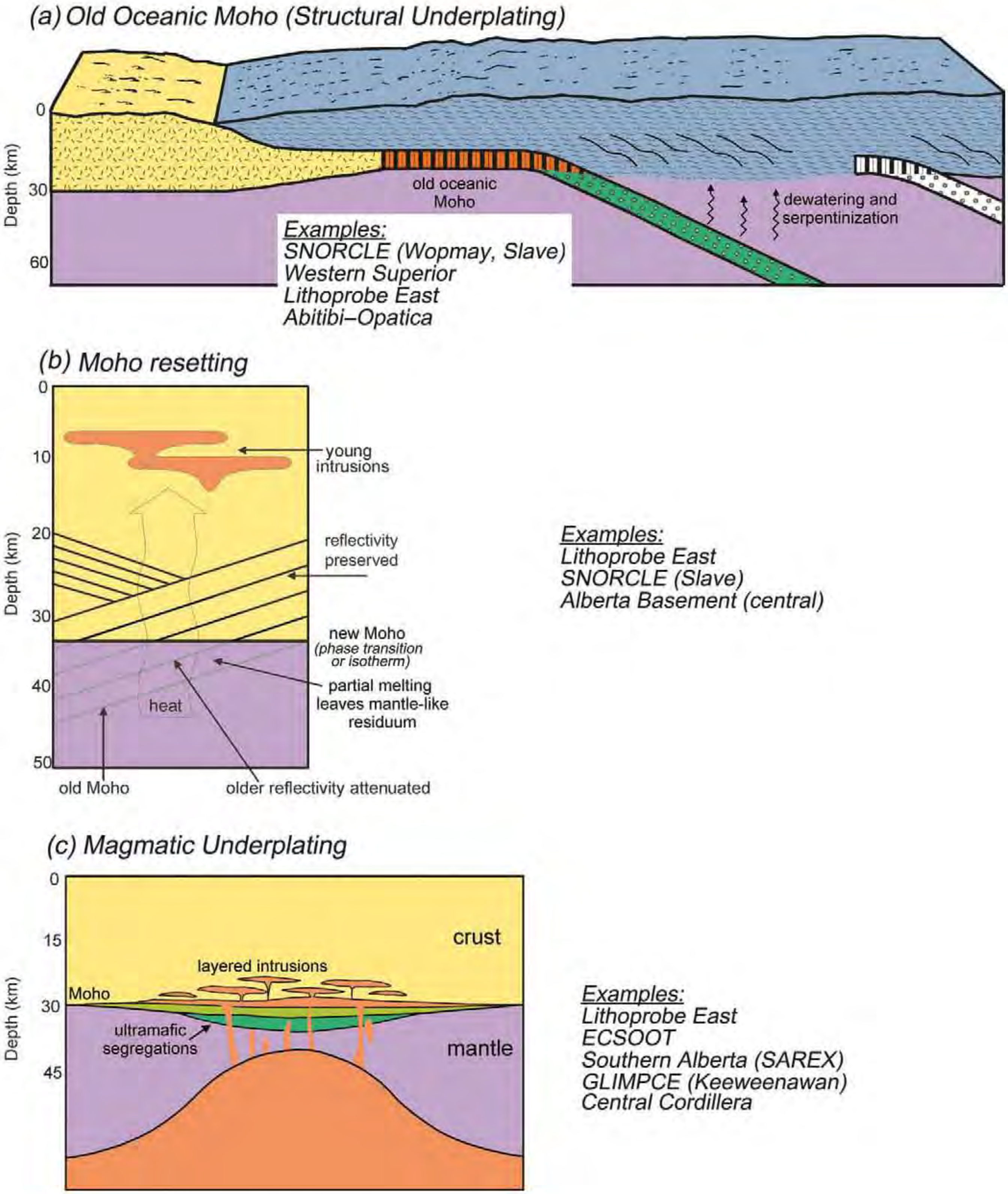
Metamorphic transition (e.g., mafic granulite to eclogite)

Eclogitization of lower crust has been invoked to explain a variety of features observed near the Moho (Ito and Kennedy 1971; Austrheim 1987; Austrheim and Mork 1988; Hynes and Snyder 1995; Fischer 2002). A relatively shallow Moho below much of the Appalachians may be the result of eclogitization of mafic lower crust so that it now assumes the seismological character of mantle (high velocity, low reflectivity). Hynes and Snyder (1995) proposed this mechanism to account for a shallow Moho separated by $\sim$10 km from a deeper reflection by a layer with mantle-like velocities. In some regions, eclogitic rocks on the surface (e.g., near the Grenville Front) have been interpreted to indicate that deeply buried crustal rocks underwent phase transformation to eclogite as a result of crustal thickening during orogeny (Eaton 2006) and that such eclogitic material could provide an isostatic balance for crustal roots in eroded orogens.

Preservation and alteration of the Moho

Preservation and alteration of the Moho depend on whether temperature, pressure, and, in some cases, fluid

Fig. 26. Models for some of the Moho configurations observed. For each model, a list of regions that may have examples of these processes is provided. (*a*) Preserved ancient oceanic Moho may form when oceanic crust is subducted. This process could be considered structural underplating and may be responsible for some of the dipping structures from the lower crust into the upper mantle that have been interpreted as paleo-subduction zones. (*b*) Resetting of the Moho may occur when the temperature rises and partial melting of lower crustal rocks leaves a residuum with mantle-like properties. This process may provide an explanation for some of the reflections that dip into the mantle across a subhorizontal reflection Moho. (*c*) Magmatic underplating can occur when upwelling magmas are intruded into the lowermost crust. Crystal segregation can produce layering near the Moho with ultramafic rocks below and mafic rocks above.



content change over time. If conditions remain relatively stable, the position (in a vertical sense) and properties across the Moho will not change. On the other hand, if any of these parameters (depth, temperature, or fluid content) is altered, the position and (or) character of the Moho could change accordingly.

Alteration of the Moho due to depth and temperature changes

If the depth of the Moho changes, due to loading or uplift, then the temperature and pressure at the new depth may lead to the development of new minerals, for example by metamorphic reactions (e.g., gabbro to mafic granulite to eclogite), or to new properties, as in the formation of a restite as a result of partial melting. Alternatively, the depth may remain constant, but the temperature may increase, for example by upwelling of asthenospheric mantle material, which could result in partial melting and restite formation. Indeed, a combination of these factors such as raised temperature plus uplift might also occur.

Alteration of the Moho due to deformation

In addition to changes in temperature, pressure or fluid content, regional tectonism may also severely alter the Moho. Demonstrable fault offset of the Moho appears to be relatively rare; however, offset may occur in both extensional (Cook et al. 1988) and compressional (Eaton et al. 2000) environments. Whether Moho offset is rare because it does not occur often in nature or because the seismic data quality and resolution are often insufficient to detect faulting is not known.

In contrast, detachment of lower crustal rocks at, or slightly above, the Moho appears to be very common (Cook 2002). Reasons for this are the followings. First, because the Moho is characterized by a substantial seismic-velocity change, which in turn represents a change in mineralogical composition, it probably also corresponds to a change in rheological properties (e.g., Handy 1994; Cook 2002). Second, the lower crust will commonly be mechanically weaker (more plastic) than the upper crust and will, therefore, tend to localize regional detachment structures, whether extensional or contractional (e.g., Cook 2002; Eaton 2006).

Alteration of the Moho due to fluid migration

Influx of fluids may substantially alter the mineralogy of the lower crust and upper mantle. For example, dewatering of subducted lithosphere in modern convergent margins has been proposed as a mechanism for reducing the velocity contrasts between the lower crust and upper mantle by causing serpentinization of the upper mantle (ANCORP Working Group 1999; Bostock et al. 2002). Observations of a nonreflective Moho above reflections interpreted to be from a Paleoproterozoic subduction zone may represent an analogous environment that is preserved beneath the western portion of the Wopmay Orogen (Fernandez-Viejo et al. 1999; Cook and Vasudevan 2003).

Does the geophysical Moho coincide with the crust–mantle transition?

The Moho is interpreted from geophysical data. It is caused by a contrast in physical properties, specifically seismic velocity, which implies an associated contrast in lithology. However, as noted by a number of authors (e.g., Ito and Kennedy 1971; Hynes and Snyder 1995; Cook 2002), in situ modification of lower crustal rocks may allow for changes in properties that could account for the geophysical transition but could also preserve pre-existing characteristics (e.g., structures, fabric, possibly some crustal lithology) below it. In such cases, as well as others described here, the geophysical boundary may map a metamorphic or igneous transition that was overprinted onto older structures. In a tectonic sense, therefore, the transition from the crust to the mantle could be considered to be a deeper level.

Such a relationship between a shallow geophysical Moho that delineates a boundary between rocks that had a similar tectonic origin and a deeper transition between rocks of substantially different origin is analogous to characteristics of some ophiolite complexes in which a ‘‘seismic Moho’’ (sometimes called the ‘‘geophysical Moho’’) and a ‘‘petrologic Moho’’ have been described (e.g., Moores 1982). In ophiolites, the ‘‘seismic Moho’’ is the compositional change from gabbroic rocks to cumulate ultramafic rocks (harzburgites) that formed by crystal fractionation. The ‘‘petrologic Moho’’ is a deeper contact between the ultramafic cumulates and tectonized ultramafic rocks that display a structural fabric and variable lithology (e.g., dunite, other peridotite, chromite, etc.). Accordingly, the geophysical Moho in these cases represents a continuum from the cumulate lower crustal rocks and the petrologic Moho represents a major tectonic boundary.

The available data in Canada and elsewhere consistently display variations that can occur over relatively short lateral distances (tens of kilometres or less) as well as a variety of configurations between lower crustal reflections, the Moho, and upper mantle reflections. An implication of the observation of varied and complex lower crust Moho – upper mantle geometry is that the crust–mantle transition is similarly complex and variable. This in turn leads to the conclusion that, in contrast to the oceanic realm, the continental Moho is neither a simple boundary nor likely to be the same everywhere. Furthermore, it appears that, in a number of areas, the geophysical boundary may be superimposed onto older crustal fabric by thermal, metamorphic, and (or) mechanical processes with a consequence that old crustal rocks and structures beneath the geophysical Moho may be preserved.

Conclusions

Analyses and comparisons of data collected during the Lithoprobe and associated projects in Canada lead to the conclusion that the continental geophysical Moho is a deceptively simple feature. It has a variety of signatures at different scales that preclude a single, universally applicable interpretation. While the large-scale characteristics of the Moho are well known — it is a relatively abrupt refraction velocity contrast and typically displays a dramatic downward decrease in seismic reflectivity — its origin is perhaps best determined by careful analyses of its structural details, which are complex and varied. Within Canada, it appears that the geophysical Moho may be old and perhaps remain from the time the crust formed in some areas, whereas elsewhere it is a relatively young feature that was superimposed onto older crustal fabric.

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