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Composition of the crust in the Grenville and Appalachian Provinces of North America inferred from V_P/V_S ratios

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Abstract. We use the ratios between *P* and *S* wave velocities (V_P/V_S), derived from seismic refraction data, to infer the composition of the crust in the Grenville and the Appalachian Provinces of North America. The crust exhibits V_P/V_S increasing with depth from 1.64 to 1.84; there is a clear distinction between the Grenville Province (average V_P/V_S =1.81) and the Appalachian Province (average V_P/V_S =1.73) which persists at all depths. The boundary between these provinces is east dipping extending for 100 km east of the Champlain thrust. In the Appalachian Province the increase in V_P/V_S ratios with depth from 1.67 to 1.74 ± 0.02 may reflect a normal decrease of silica content in the continental crust. In the Grenville Province beneath the Central Granulite Terrane, an anomalous V_P/V_S ratio of 1.82 ± 0.02 is observed extending to a depth of 10 km; this correlates with the abundance of Ca-plagioclase in the Marcy Anorthosite. At greater depth (15-20 km), where seismic lamination and high electrical conductivity is observed, V_P/V_S is 1.84 ± 0.02 and correlates with the Tahawus Complex, a layered mafic intrusion. Within the 25-km-thick lower crust of the Grenville Province the V_P/V_S is 1.84 ± 0.02 and P-velocity is 7.0 ± 0.1 km/s, which are typical for plagioclase-bearing rocks (gabbro-norite). The high V_P/V_S ratio in the Grenville Province has not been reported in crust of any other age. Since the Grenville Province contains 75% of the world's known anorthosites, high V_P/V_S ratio is related to high plagioclase. We suggest that the composition of the Grenville lower crust was significantly modified by the emplacement of the anorthosites in the mid-Proterozoic.

Introduction

Seismic refraction profiles collected over the past 40 years have provided measurements of the *P* wave structure of the crust on a global basis. The distribution of these measurements is sufficiently wide to define a characteristic *P* wave velocity structure for different tectonic provinces such as Precambrian shields, rifts and continent-continent collision zones. Furthermore, inferences regarding the composition of the deep crust are possible based on a comparison of field and laboratory measurements of *P* wave velocities [*Meissner*, 1986; *Mooney and Meissner,* 1991, 1992; *Holbrook et al.*, 1992; *Christensen and Mooney*, 1995; *Rudnick and Fountain,* 1995]. However, the non uniqueness of the relationship between *P* wave velocity and composition is well known; therefore, it is important to determine the *S* wave velocity structure so that further constraints may be placed on deep crustal composition.

In this paper, we use seismic refraction data to derive the ratio between *P* and *S* wave velocities (V_P/V_S) in the Grenville and Appalachian Provinces of North America. Since the V_P/V_S ratio, rather than V_S alone, is most diagnostic of crustal composition, we have chosen to discuss this ratio in some detail. We note that crustal cross sections of the V_P/V_S ratio often show more lateral variations than either V_P or V_S cross sections alone [e.g., *Kern et al.*, 1991, 1993; *Walther and Flueh,* 1993]. In this study, we find that whereas small-scale (several kilometers) V_P/V_S anomalies may be artifacts of the data interpretation, a direct comparison of the *P* and *S* wave travel times demonstrates that larger-scale (tens of kilometers) V_P/V_S anomalies within the crust are not artifacts and hence may be attributed to actual variations in the composition of the crust.

Compositional differences between the Grenville and Appalachian Provinces that have been determined from geological mapping can be imaged in the third dimension by V_P/V_S modeling. We use crustal V_P/V_S ratios to determine the depth to which differences in the Grenville and the Appalachian Province persist and to determine how far the eastern edge of the Grenville crust can be traced beneath the Appalachian Terranes. From a more general point of view we seek to infer the evolutionary processes of Proterozoic crust in relation to the 1.3 Gyr old anorthosite massifs in the Grenville Province.

The data we analyze here, the Ontario-New York-New England profile (O-NYNEX), are the result of a refraction/wide-angle seismic line acquired by the U.S. Geological Survey (USGS), the U.S. Air Force Geophysical Laboratory (AFGL) and the Geological Survey of Canada (GSC) during the fall of 1988. This 650-km-long east-west trending profile crosses roughly perpendicular to strike the

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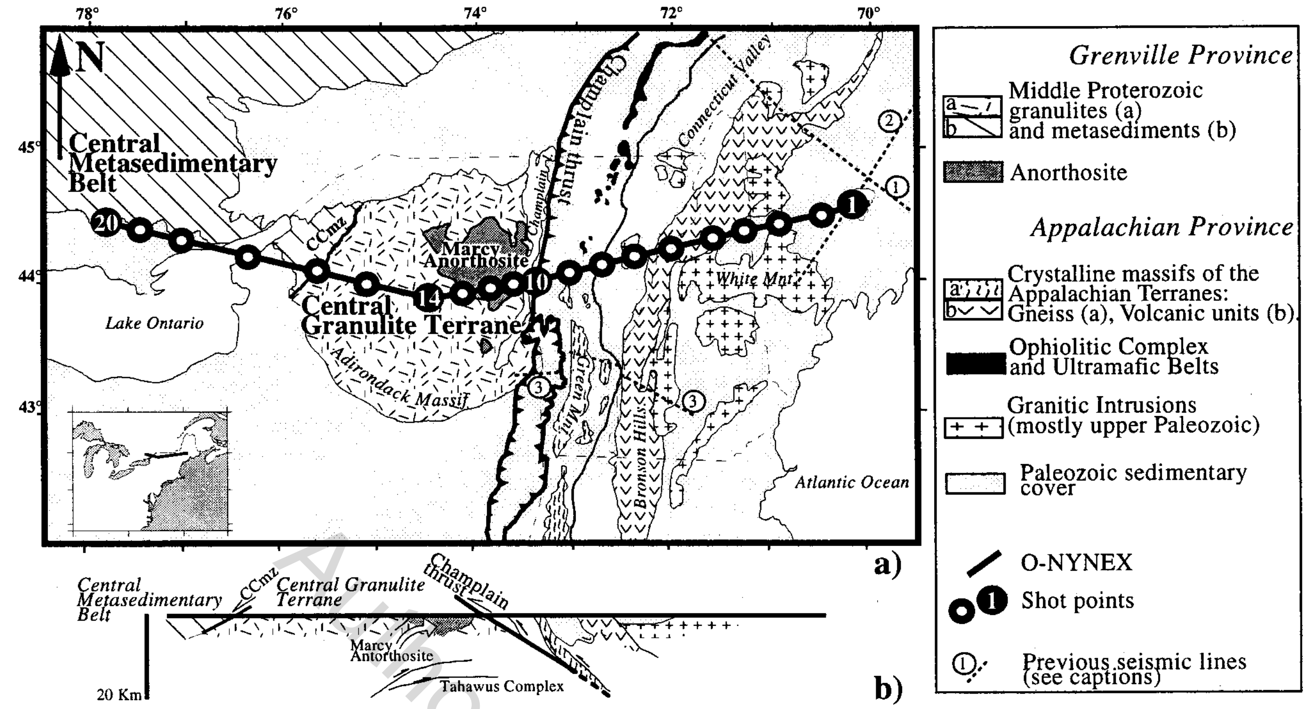

Figure 1. (a) Simplified geologic map [after *Williams*, 1978; *McLelland and Isachsen*, 1986] of the southeastern Grenville Province and north Appalachian Province, showing the location of the O-NYNEX refraction seismic profile. (b) Simplified cross section showing the projection at depth of the exposed geologic units. CCMZ=Carthage-Colton mylonite zone. Previous seismic profiles are shown by the dashed lines: (1) the Quebec-Maine seismic reflection and refraction profiles [*Spencer et al.*, 1989]; (2) the USGS refraction profile along the axis of the Merimack Synclinorium [*Hennet et al.*, 1991]; (3) the southern Vermont and Adirondack deep seismic reflection profile collected by Consortium for Continental Reflection Profiling (COCORP) [*Ando et al.*, 1984].

Proterozoic craton of southern Ontario, the Adirondack Mountains, and the New England Appalachians (Figure 1). In this paper, exceptionally clear *S* wave phases generated from twenty explosive sources and recorded by vertical component geophones have been analyzed. Previous analysis of these data was limited to *P* wave ray-tracing and travel time inversion modeling [*Hughes and Luetgert*, 1991, 1992; *Zelt and Forsyth*, 1994; *Zelt et al.*, 1994]. Average crustal V_P/V_S ratios had been previously derived along this profile from comparison of *P* and *S* arrival times [*Hughes and Luetgert*, 1991] and from the ratio between the *P* wave velocity, given by seismic refraction modeling, and the *S* wave velocity, given by teleseismic modeling [*Hughes and Luetgert*, 1992].

Geological Setting

The O-NYNEX profile traverses the southeastern promontory of the Grenville Province and the adjacent western New England Appalachian orogen (Figure 1). The Grenville Province records a middle Proterozoic thermal pulse that led to the emplacement of anorthosite massifs that comprise 75% of the world's known anorthosites [*Condie*, 1982]. The subsequent Grenville orogeny was a metamorphic, tectonic, and magmatic mountain building episode that accreted crystalline basement to the Archean craton of North America. The orogeny culminated around 1.1 Ga with pervasive northwest directed compression [*Moore*, 1986]. A later phase of extension was initiated in eastern North America during the Late Proterozoic with the formation of the Iapetus Ocean [*Rankin*, 1976]. The Ordovician Taconic orogeny was concomitant with the closing of the Iapetus Ocean and the accretion of the western part of the Appalachians to the continent. The last regional thermal event that affected eastern North America was related to the Mesozoic rifting of the Alleghenian orogen and the opening of the Atlantic Ocean.

Grenville Province

The Grenville Province is exposed in Canada and the eastern United States along a 1600-km strip that separates the Archean Superior craton from the Paleozoic Appalachians. The Grenville Province is mainly composed of tonalitic gneisses which are, in large part, reactivated Archean gneisses [*Condie*, 1982]. Minor amounts of gabbro, diabase, and anorthositic rocks are intruded into the gneisses and exhibit a metamorphic imprint of amphibolite-granulite facies, related to the Grenville orogenesis [*Wiener et al.*, 1984; *McLelland and Isachsen*, 1986]. Most of the anorthosites are characterized by positive gravity anomalies, suggesting the existence of mafic roots [*Thomas*, 1990]. Our seismic profile crosscuts one of the largest meta-anorthosite massifs, the Marcy Anorthosite, located within the Central Granulite Terrain (Figure 1). Associated with the meta-anorthosites are small quantities of mafic rocks (gabbros and norites) [*DeWaard and Romey*, 1969], ultramafic sheets and dikes [*Ashwal*, 1982], and significant quantities of silicic rocks (mafic syenites, monzonites, and quartz syenites) that tend to form envelopes around the meta-anorthosites [*McLelland*, 1989]. The consanguinity between the silicic and anorthositic suite is still an open debate [*Ashwal*, 1993].

The Central Metasedimentary Belt and the Central Granulite Terrane [*Lumber et al.*, 1990; *Culotta et al.*, 1990] are two tectonostratigraphic units having regional extent in the Grenville Province (Figure 1). The Central Metasedimentary Belt represents one of the few exposures of supracrustal rocks in the Grenville Province. It includes highly sheared marbles, quartzites, metaevaporites, and pelitic migmatitic gneiss that have been metamorphosed to amphibolite-granulite facies during the Grenville orogeny (1.2-1.1 Ga). The Central Granulite Terrane exposes a complex assemblage of polydeformed granitic gneiss, syenites, charnockites, migmatites, interlayered with quartzites and marble, and hornblende gneiss with localized mafic and amphibolitic interlayering [*Wynne-Edwards*, 1972; *Wiener et al.*, 1984; *McLelland and Isachsen*, 1986].

Appalachian Province

The Appalachian Province consists of the eroded core of a Paleozoic mountain chain that extends at least 3000 km from the southeastern United States to Newfoundland. The province is the trace left of three major Paleozoic orogenies (Taconic, Acadian, Alleghenian) recorded along both coasts of the North Atlantic. These orogenies can be related to a complex history of the North Atlantic region involving the opening (late Proterozoic), closing (mid-Ordovician to Permian), and reopening (Mesozoic) of an ocean basin [*Rankin*, 1976; *Taylor*, 1989]. The Taconic orogeny is recorded in the exposed terranes along the eastern part of the O-NYNEX profile (Figure 1) and is believed to be an episode of arc-continent collision [*Stanley and Ratcliffe*, 1985]. The Appalachian Terrane is exposed here as a stack of west verging imbricated slices of flysch and forearc sediments (Champlain Valley), volcanic units (Bronson Hill Anticlinorium), ultramafics (Vermont ultramafic belt), and high-grade metamorphic rocks (Central Maine Synclinorium) (Figure 1). Slices of Grenville basement crop out in the Green Mountains and in the Berkshire Highlands [*Tilton et al.*, 1960; *Faul et al.*, 1963; *Ratcliffe and Zartman*, 1976] (Figure 1). They are composed of well-layered, garnet-rich, biotite-plagioclase-quartz gneisses, hornblende-biotite granitic gneisses, and massive quartzite [*Doll et al.*, 1961; *Stanley and Ratcliffe*, 1985]. They underwent greenschist retrograde metamorphism during Taconian and Acadian orogenies [*DellaRusso and Stanley*, 1986].

Previous Geophysical Studies

Previous geophysical models of this area are mainly based on the interpretation of reflection and refraction seismic data, teleseismic receiver function analysis, gravity modeling, and geoelectrical data. The difference in seismic velocity structure between the Grenville and the Appalachian Provinces was established over a decade ago [*Taylor and Toskoz*, 1979]. The suture between these two tectonic regions has been investigated by a number of geophysical studies [*Ando et al.*, 1983; *Brown et al.*, 1983; *Mooney and Braile*, 1989; *Phinney and Roy-Chowdhury*, 1989; *Hughes and Luetgert*, 1991; 1992; *Zelt et al.*, 1994]. The crustal *P* wave velocity structure along the whole O-NYNEX profile is given by *Hughes and Luetgert* [1991, 1992]. *Zelt and Forsyth* [1994] have modeled the *P* wave velocity structure between shot point 20 and 14 (Figure 1). The previous *S* wave studies are based on long-period seismogram analysis and on receiver function inversion [*Levin et al.*, 1995; *Owens*, 1987].

The Grenville Province has a crustal thickness of ~45 km with average *P* wave velocities of 6.3, 6.6, and 7.0 km/s for the upper, middle, and lower crust, respectively (Figure 2a). Seismic reflection images show crustal reflectivity down to the Moho [*Hall and Quinlan,* 1994]. In the upper middle crust, west dipping structures are consistent with the vergence of the exposed tectonic lineaments (i.e., the Carthage-Colton mylonite zone (CCmz), Figure 1) related to the Grenville orogeny [*Culotta et al.*, 1990; *Zelt et al.*, 1994]. In the upper crust, beneath the Adirondack Mountains, a 7-km-thick upper crustal body (V_P= 6.6 km/s) was correlated with the Marcy Anorthosite [*Hughes and Luetgert,* 1991]. On the basis of gravity modeling, the main anorthosite body was believed to be 4-5 km thick [*Simmons*, 1964], with possible roots to a depth of 10-15 km. The Precambrian anorthosites in the Adirondack Mountains also correlate with low heat flow values due to a low content of radioactive elements [*Birch et al.*, 1968]. Teleseismic data from the area of these anorthosite complexes show *P* (and *S*) wave velocities 0.3 (and 0.1) km/s higher than average values found elsewhere in the Grenville Province [*Levin et al.*, 1995].

At the boundary between the middle and lower crust, *Hughes and Luetgert* [1992] modeled a dome-shaped high-velocity body (V_P=7.1 km/s) referred to as the Tahawus Complex (Figure 2a). The Tahawus Complex was also imaged as a thick (2 to 3 s two-way travel time) laminated body by near-vertical seismic reflection data [*Brown et al.*, 1983; *Klemperer et al.*, 1985] and as a high velocity body by teleseismic receiver studies [*Owens*, 1987]. It is underlined by a high-conductivity layer [*Connerney et al.*, 1980]. Moreover, it seems to correspond to an anomalously high *S* wave velocity (3.9-4.0 km/s) body in the midcrust that overlies a low-velocity lower crust [*Owens*, 1987].

P wave velocities in the lower crust along the O-NYNEX transect are in the range of 6.8-7.2 ±0.2 km/s according to *Hughes and Luetgert* [1991, 1992]. *Zelt and Forsyth* [1994] modeled a *P* wave velocity of 7.4 ±0.1 km/s at the bottom of the lower crust between shot points 20 and 14 (Figure 1) to match unreversed refracted phases recorded from shot point 20.

In the Appalachian Province, *P* wave ray-trace modeling [*Hughes and Luetgert*, 1991] shows that crustal thickness ranges from 36 km in the east to 40 km in the west (Figure 2b). Recent tomographic inversions of refraction and teleseismic *P* wave arrivals indicate that the Proterozoic Grenville Province has a *P* wave velocity 0.2-0.3 km/s higher than the Paleozoic Appalachian Province [*Levin et al.*, 1995].

The westernmost edge of the Appalachians, the Grenville Ramp (Figure 2), has been imaged as an east dipping zone of reflections that is also expressed as a pronounced Bouguer gravity gradient [*Ando et al.*, 1984]. The nappe of slices of basement and sedimentary cover is thought to be responsible for the reflectivity of this zone [*Stewart et al.,* 1986]. The Grenville Ramp also correlates with a major lateral velocity change in the upper and middle crust (Figure 2): from 6.5 km/s in the Grenville Province on the west side of the ramp to 5.9-6.4 km/s in the Appalachian Province on the east side of the ramp [*Hughes and Luetgert,* 1991]. This ramp extends down to depths of 20 km and can be connected to the Champlain thrust (Figures 1 and 2).

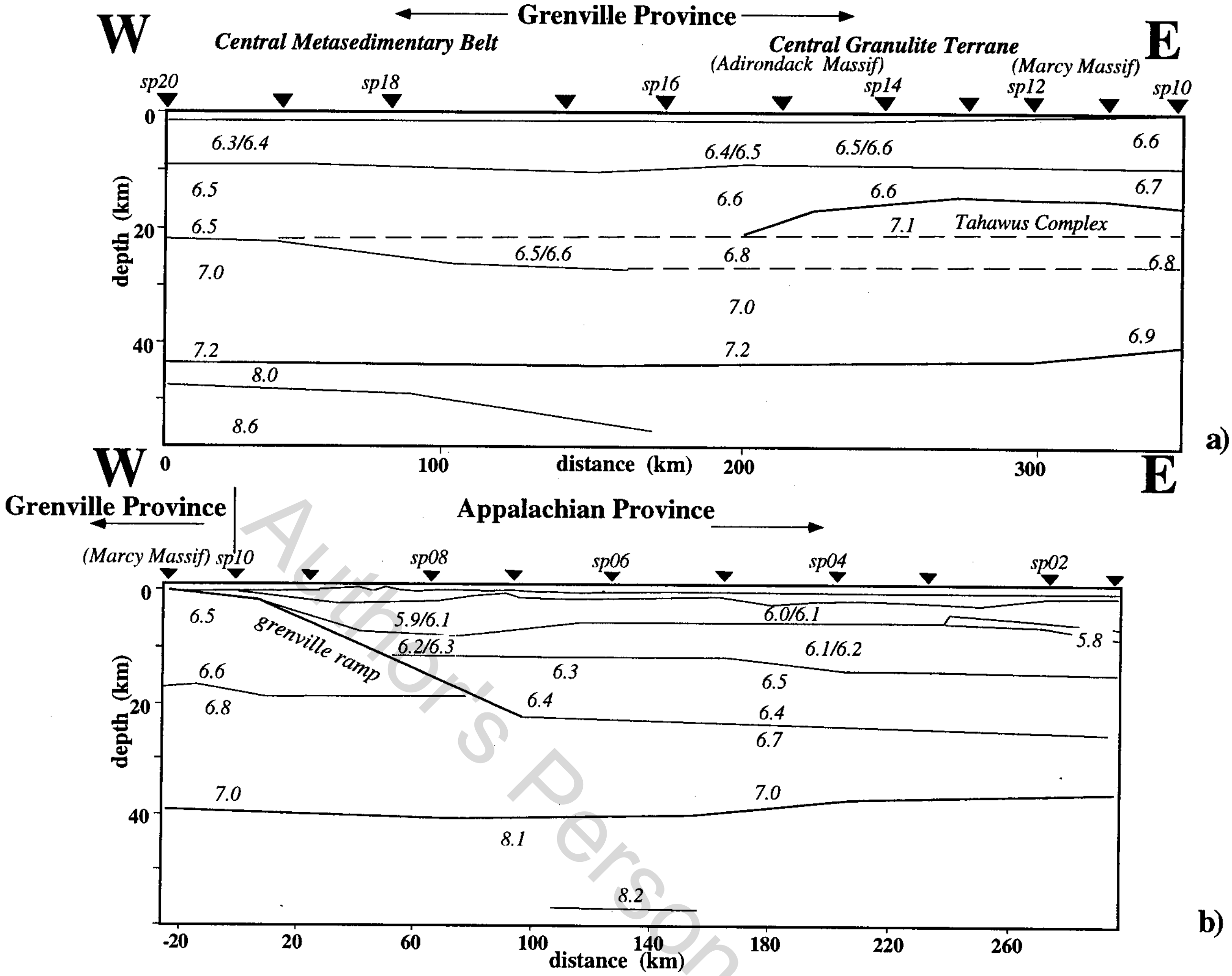

Figure 2. *P* wave velocity models as published by *Hughes and Luetgert* [1991, 1992] along the O-NYNEX profile. Two separate models have been published: (a) the first is in the Grenville Province, includes shot points 20-10 and was obtained by inversion technique; (b) the second includes shot points 11-1 in the Appalachian Province and was obtained by forward modeling.

Description of the Principal *S* Wave Phases and of the T_S/T_P Ratios

The O-NYNEX seismic refraction data provide a unique opportunity to derive both *P* and *S* wave seismic velocity structure in the Grenville and Appalachian Provinces. The high data quality is mainly due to relatively dense (800 m) trace spacing and the high signal-to-noise ratio. Despite the fact that only vertical component geophones were deployed, remarkable *S* wave energy has been recorded (Figures 3 and 4). Surface waves, propagating with an apparent velocity of ~2.5 km/s represent the strongest noise interfering with the *S* wave arrivals at short offset distances. In a few cases (e.g., Figure 4), band-pass frequency filtering (8-10 Hz) and frequency-wave number (f-k) filtering (velocity bounded between 2.9 and 5.0 km/s) were used to attenuate the surface waves. The f-k filtering was problematic due to typical variable trace spacing. For short receiver-source distances, f-k filtering produced spatial aliasing of later phases. Coherency filtering was more successful in improving the signal-to-noise ratio. We applied coherency filtering using two different reduction velocities. A velocity of 3.46 km/s was used up to distances of 100 km in order to improve signal-to-noise ratio of crustal phases; at larger distances a reduction velocity of 4.62 km/s was used to improve mantle phases. We displayed the final time sections using a reduction velocity of 4.62 km/s to facilitate identification of deep crustal and mantle phases (S_mS and S_n).

General Features of the Correlated *S* Wave Phases

The record sections shown in Figures 3 and 4 are representative of the *S* wave data acquired in the O-NYNEX experiment and also show typical features of the wave field along the profile. In the time domain, five principal phases labeled S_g, S_iS, S_i, S_mS, and S_n, have been identified (Figures 3 and 4). The high signal-to-noise ratio resulted in arrival time uncertainties of only ±0.1 and ±0.15 s for waves propagating from shot points within the Grenville and the Appalachian Terrane, respectively (e.g., Figures 4a, b, and 4d). Refracted phases from the lower crust, S_i, and from the upper mantle, S_n, are usually very weak and show larger uncertainties (Figure 4d).

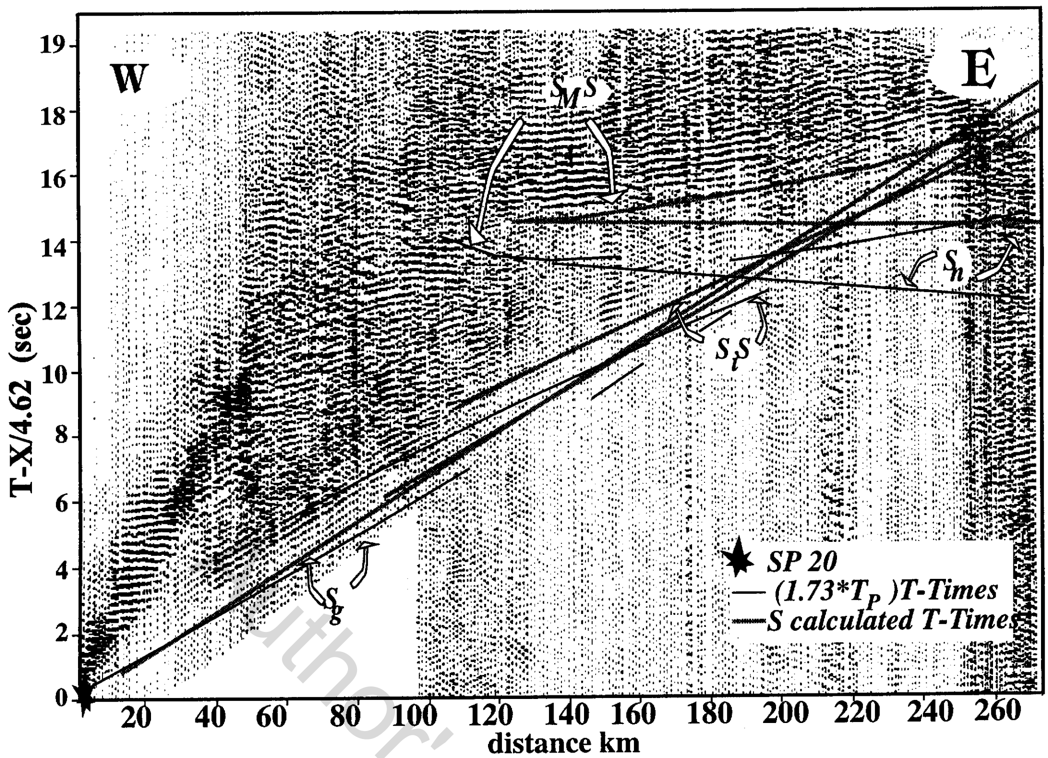

Figure 3. Record section for shot point 20 in the Grenville Province plotted in normalized format with distances relative to the shot point. A reduction velocity of 3.46 km/s was used. This record section is representative of the high quality *S* wave data of the O-NYNEX seismic refraction line . Note the delay of the *S* wave signal with respect to an arrival time of T_S=1.73*T_P. See text for the discussion.

The S_g phases propagate in the upper crust with an apparent velocity of ~3.46 km/s, and they can be followed up to source-receiver distances ranging from 100 to 160 km. At source-receiver distances greater than 100 km, reflections (S_iS) from the top of the lower crust are observed. At large distances the asymptote of the S_iS phase indicates an average velocity for the upper and middle crust of ~3.6 km/s. Along this travel time branch, short segments of coherent energy (e.g., Figure 4a) are assumed to be spurious phases related either to diffractions or out-of-plane signals; therefore they have not been considered.

The Moho reflected phases, S_mS, consist of 1-2 sec long energy packages (Figures 3 and 4) with critical points at distances ranging from 100 to 120 km from the shot point. The S_mS travel time branch can sometimes be clearly followed out to distances of 280 km from the source (Figures 3 and 4). *S* wave refracted energy from the upper mantle, S_n, travels with an apparent velocity of ~4.6 km/s but was recorded only from a few shots (Figures 3 and 4d).

Comparison Between *P* and *S* Waves in the Time Domain: T_S/T_P Ratios

Assuming that *P* and *S* waves have the same travel path, the comparison between *P* and *S* wave arrival times (T_P and T_S) gives a rough estimate of the average V_P/V_S ratios of the media. Nevertheless, the higher the V_P/V_S ratio, the greater are the differences in travel paths between *P* and *S* waves. We calculate that for V_P/V_S~1.8 the difference between the *P* and the *S* travel paths is less than 3 kilometers and therefore has no significant influence on the determination of T_S/T_P ratios at our scale of interest. Both T_S/T_P and V_P/V_S ratios are directly proportional to Poisson's ratio of a rock. If the T_S/T_P ratio analysis is the most objective way to show variations in Poisson's ratio within the media, V_P/V_S modeling represents the "migration" at depth of the T_S/T_P ratio values.

On the *S* wave time window we have plotted the expected *S* wave arrival time (Figure 3), that is, the *P* wave arrival time multiplied by 1.732, which corresponds to the commonly assumed average T_S/T_P ratio for the crust. Delayed *S* wave phases indicate a T_S/T_P ratio greater than 1.732 (and vice versa). Laboratory measurements for crystalline rocks indicate that T_S/T_P ratios fall in the range of 1.45-1.9. If the observed *S* wave arrival time gives a T_S/T_P ratio beyond this range, we infer that the P and S phases do not originate from the same boundary.

For each of the three detected phases (S_g, S_iS, S_mS) we have plotted the corresponding T_S/T_P ratio versus model-coordinate distance (Figure 5). The diagram shows that the commonly assumed value of 1.73 is only found for the S_mS phase (that gives the average T_S/T_P value for the whole crust) in the Appalachian crust. We can see that Poisson's ratio in the crustal section varies at two different scales. Small scale (1-10 km) variations are indicated by T_S/T_P ratio variations along a fixed travel time branch. Larger-scale (10-100 km) variations are indicated by a general increase of the T_S/T_P ratio (from average values of 1.7-1.82) for rays penetrating the Grenville Province. The shaded area in Figure 5 shows that the main change in the T_S/T_P ratio occurs 50 km east of shot point 10, which is located on the Champlain thrust, the mapped western limit of the Appalachian Terranes (Figure 1). The presence of slices of Grenville basement east of the Champlain thrust [*Stanley and Ratcliffe*, 1985] complicates the concept of a simple boundary between the two provinces. Since the high T_S/T_P ratios seem to be associated with the Grenville Province, our data show that the Grenville Province has to extend farther east of the Champlain thrust, into the Appalachian Province either as autochthonous crust below the Grenville ramp, or as allochthonous thrust sheets [*Stanley and Ratcliffe*, 1985].

S Wave Modeling

To model the *S* wave velocity structure of the crust, we joined the two separate *P* wave crustal models of *Hughes and Luetgert* [1991, 1992] for the Grenville and Appalachian Provinces and used two-dimensional ray-trace modeling [*Cerveny et al.*, 1977; *Luetgert*, 1988] to obtain a uniform *P* wave velocity model. Small adjustments on the *P* wave velocity were required to overcome mismatches in the two published *P* wave models at the boundary of the Grenville and Appalachian Provinces (compare Figure 2 and Plate 1a).

The use of vertical-component data to derive a *S* wave velocity model requires a discussion of potential errors and uncertainties. *S* waves are generated from explosive sources as *P*-to-*S* conversions nearby the shot point. Because in our calculation we do not consider travel times of converted waves, this could affect the Vp/Vs ratios. Candidates for an energetic *P*-to-*S* conversion nearby the source are (1) the fracture radius of the shot hole, (2) the free surface (upgoing *P* wave reflected at the surface results in a downgoing *P* to *S* converted wave), and (3) the sediment-crystalline basement interface (for shot holes drilled into shallow sedimentary basins). We calculate that in these cases the travel time before the conversion to *S* wave is small enough to be ignored. This allows us to consider the *P*-to-*S* wave generated near the source as a source-generated *S* wave. Nevertheless, the vertical component seismograms might record *S*-to-*P* or *P*-to-*S* converted energy for waves traveling from the source to the receiver. In particular, the presence of a strong impedance contrast boundary (i.e., a sedimentary layer on top

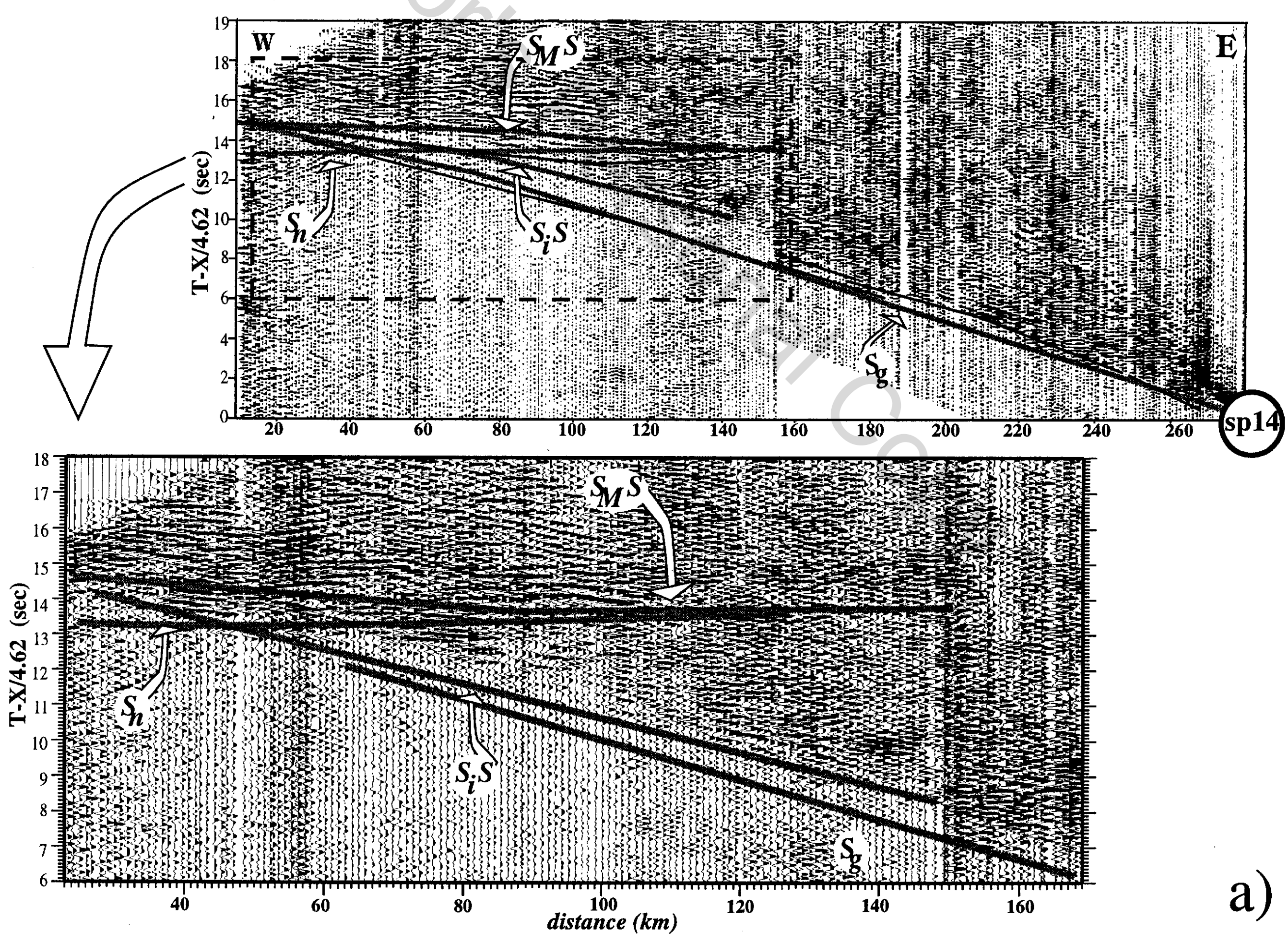

Figure 4. *S* wave signals for shot points sorted from west to east and plotted with distances relative to shot point 20, at the western end of the line: (a) shot point 14; (b) and (c) shot point 10; (d) shot point 1. The large arrows points to a close up of the area highlighted by the dashed rectangle. Gray lines indicate calculated *S* wave arrival times. Black thin lines indicate *P* wave arrival times multiplied by 1.73. *S* wave data processing included frequency band-pass, f-k (frequency-wave number) and coherency filtering. The quality of the recorded *S* wave signals increases toward the west since ray paths crosscut the Grenville Provinces.

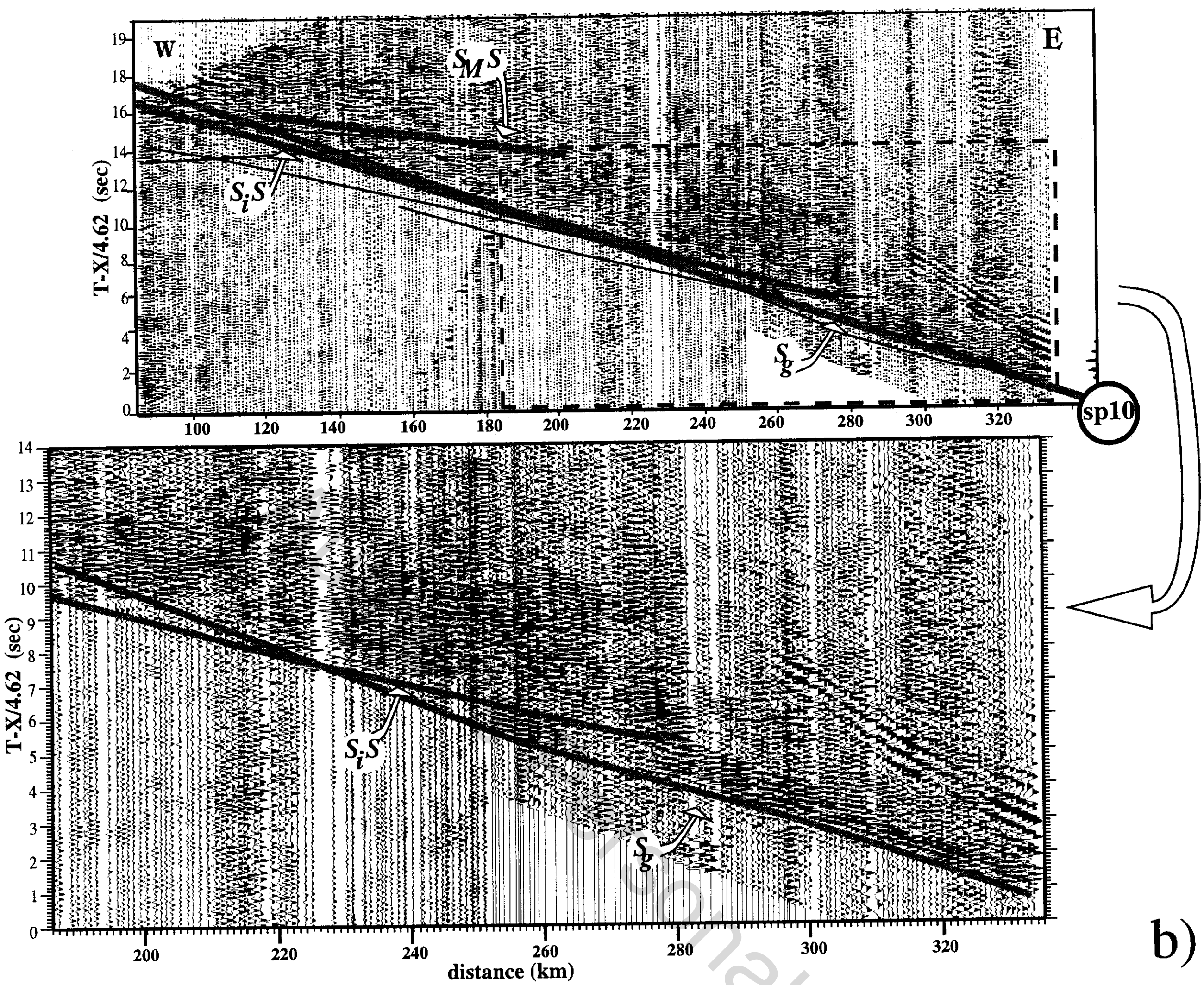

Figure 4. (continued)

of crystalline basement) can generate high-amplitude *P*-to-*S* arrivals that precede the true *S* wave arrival [*Andrews et al.*, 1985].

A number of examples of vertical component *S* wave record sections are published in the literature [e.g., *Walther and Flueh*, 1993; *Musacchio et al.*, 1995; *Barth and Klemperer*, 1993], and some of these authors have derived *S* wave crustal models from vertical component data [e.g., *Walther and Flueh*, 1993; *Musacchio et al.,* 1995]. These studies demonstrate that there are no significant differences between the arrival time of *S* wave phases on vertical- and horizontal-component recordings in areas where the topmost sedimentary layer has no significant thickness (i.e., in areas of exposed crystalline rocks). In fact, in order to have a significant influence on travel times, a sedimentary layer would have to be more than 500 m thick, along the entire profile. In this extreme case, there would be a systematic error in the interpretation of the *S* wave structure along this 650-km-long profile, but it would still be possible to compare relative values along the crustal cross section. Additional confidence in our *S* wave modeling results from the excellent agreement between the modeled near-surface seismic velocities near the shot points and the *S* wave velocities measured on the corresponding rock samples.

In the *S* wave model we assume that the observed *P* and *S* wave energy was generated from the same seismic boundaries and that anisotropy is negligible. The *P* wave structural model has been kept fixed, and only the *S* wave velocities have been adjusted to match the observed arrival times.

The high ray coverage within the model results in good resolution of depth and velocity for all interfaces. On the basis of travel time modeling the *P* wave model derived by *Hughes and Luetgert* [1991; 1992] had an uncertainty of ±0.05 and ±0.2 km/s for the velocity in the upper-middle and lower crust, respectively. The higher uncertainty for the velocity in the lower crust was due to modeling of secondary arrivals and to less dense ray coverage, as the modeling was divided into two separate sections and therefore did not include all long distance shots (Figure 2). We have improved the uncertainties on the *P* wave velocity for the lower crust by joining the two published separate models, which resulted in higher ray coverage in the lower crust (compare Figures 2 and 6). In a few cases we have identified refracted phases from the lower crust, P_i and S_i, and strengthened the constraints on the velocity of the lower crust (Figure 4d). Uncertainties in *P* and *S* wave velocities in the lower crust, inferred from our ray-trace modeling, are ±0.1 km/s. In general, observed and

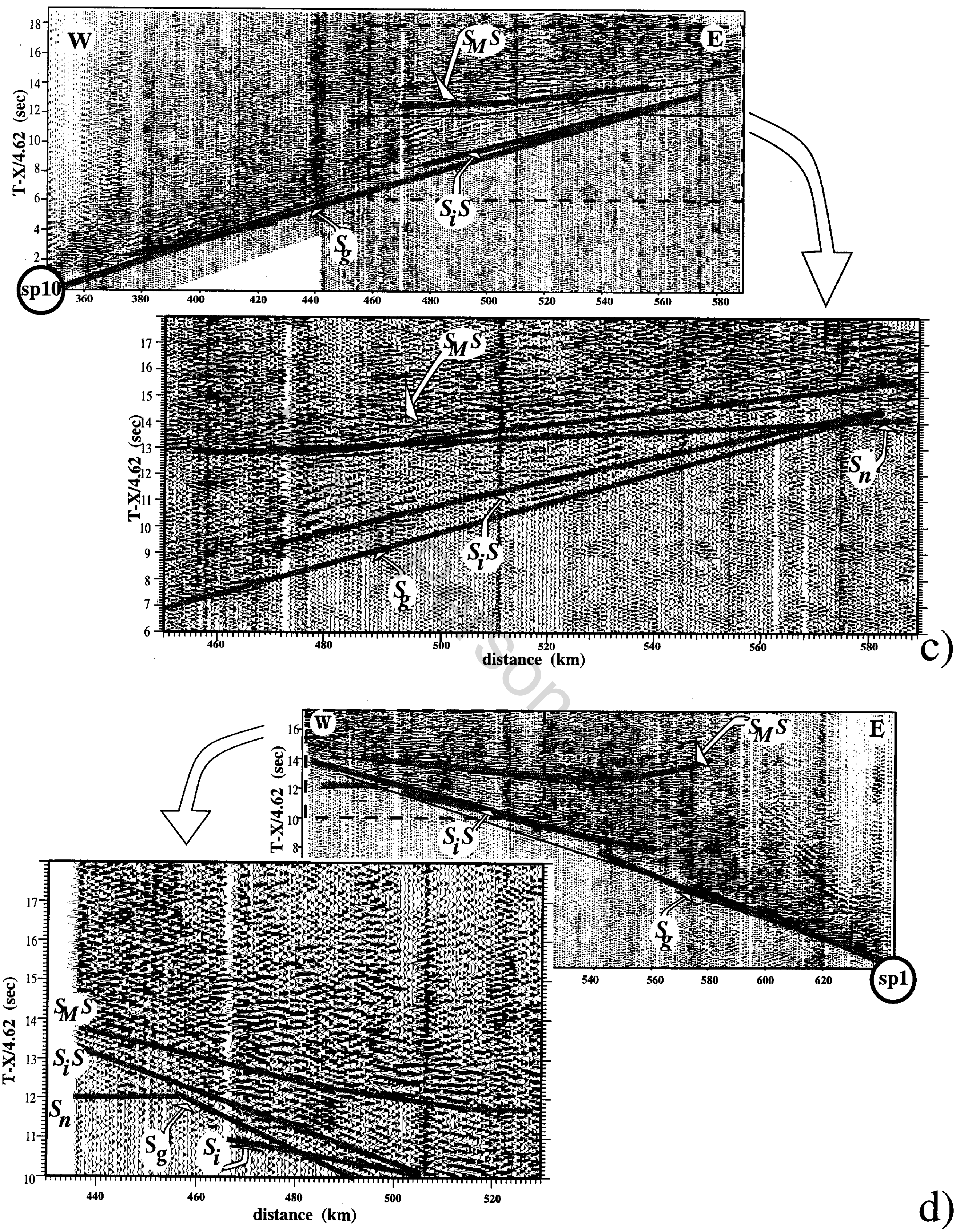

Figure 4. (continued)

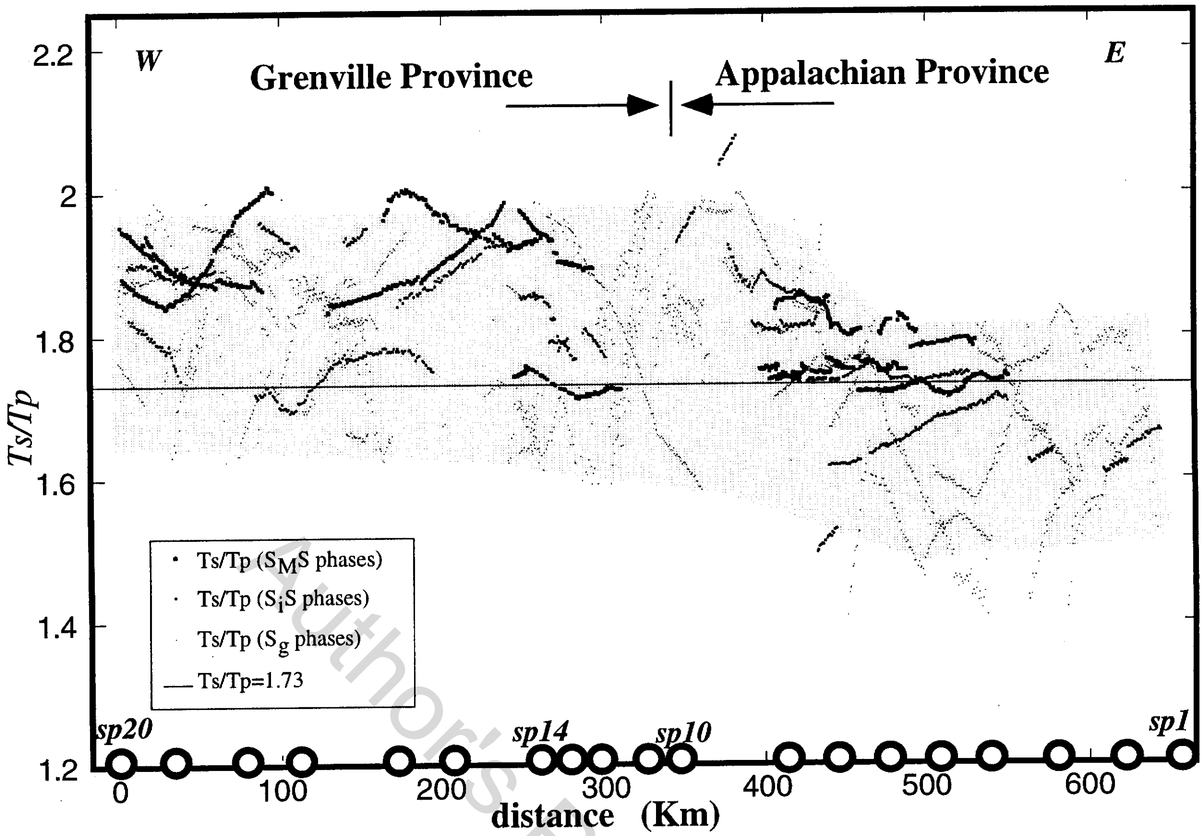

Figure 5. T_S/T_P versus model coordinate. Note the general increase of T_S/T_P ratios toward the Grenville terrain. The shaded area emphasizes the lateral change in Poisson's ratio occurs 50 km east of the boundary between the Grenville and Appalachian Province.

calculated travel times for the final *S* wave model agree to within 0.1 s or less, with no mismatches greater than 0.2 s (Figure 6). The lower signal-to-noise ratio for phases propagating in the Appalachian upper crust raises the uncertainty in the calculation of *S* wave velocity up to ±0.2 km/s. This higher uncertainty eliminates the significance of any lateral variations in Vp/Vs ratios we had found in this part of the model (see the upper 10 km in Plates 1b and 1c). Unless specified, the average uncertainties for the V_P/V_S ratios are ±0.02.

P and *S* Wave velocity models

We found that the Grenville and Appalachian crust have distinct seismic features. The Proterozoic crust of the Grenville Province exhibits high seismic velocities in both *P* and *S* wave fields (Plates 1a and 1b). *P* wave velocities range between 5.5 and 6.2 km/s, and *S* velocities range between 3.0 and 3.6 km/s in the 7-km-thick upper crust. In the 12-km-thick middle crust the seismic velocity of *P* and *S* waves ranges between 6.2-7.0 km/s and 3.5-3.9 km/s, respectively. Average *S* wave velocities in the Grenville domain have a value of 3.7 ±0.15 km/s and are consistent with values indicated by published teleseismic data [*Jordan and Frazer*, 1975].

At the Appalachian suture zone the upper and middle crust is characterized by a west verging structure, the Grenville Ramp, separating the high-velocity (V_P=6.5 km/s) Grenville Proterozoic crust from the lower velocity (V_P= 6.1 km/s) Appalachian accreted terranes (Plate 1). This ramp was modeled as a first-order discontinuity in the *P* wave velocity field by *Hughes and Luetgert* [1991], whereas it appears to be substantially smoothed in the *S* wave velocity field (Plate 1b). The structure of the ramp is reversed at all depths in the *P* wave velocity field since progressively deeper portions are sampled by shot points at successively greater offsets. The highest velocity values (~6.7 and 3.7 km/s for *P* and *S* waves, respectively) are found in the Grenville upper crust at distances between 280 and 350 km from shot point 20 (Plates 1a and 1b). They are detected by four shot points (from 13 to 10) spaced ~25 km apart. These shot points are located on the Marcy Anorthosite.

In the middle crust, beneath the Central Granulite Terrane, high-amplitude *P* and *S* wave reflections have been detected from a dome-shaped body located at a depth spanning from 15 to 20 km, coinciding with the Tahawus Complex (Plate 1). In our model the Tahawus Complex has a velocity of 7.0 and 3.8 km/s for *P* and *S* waves, respectively, and it masks *P* and *S* reflections from the top of the lower crust in the Central Granulite Terrane (Figure 6). These values are consistent with those obtained by receiver function inversion [*Owens*, 1987].

The lower crust along our 650-km-transect is modeled as a thick and laterally inhomogeneous layer with *P* wave velocities ranging from 6.8 to 7.2 km/s and *S* wave velocities ranging from 3.7 to 4 km/s, with increasing depth. The thickness of the lower crust decreases toward the east as the top of the lower crust deepens and the Moho boundary rises in the Appalachian Province (Plate 1). The low *S* wave

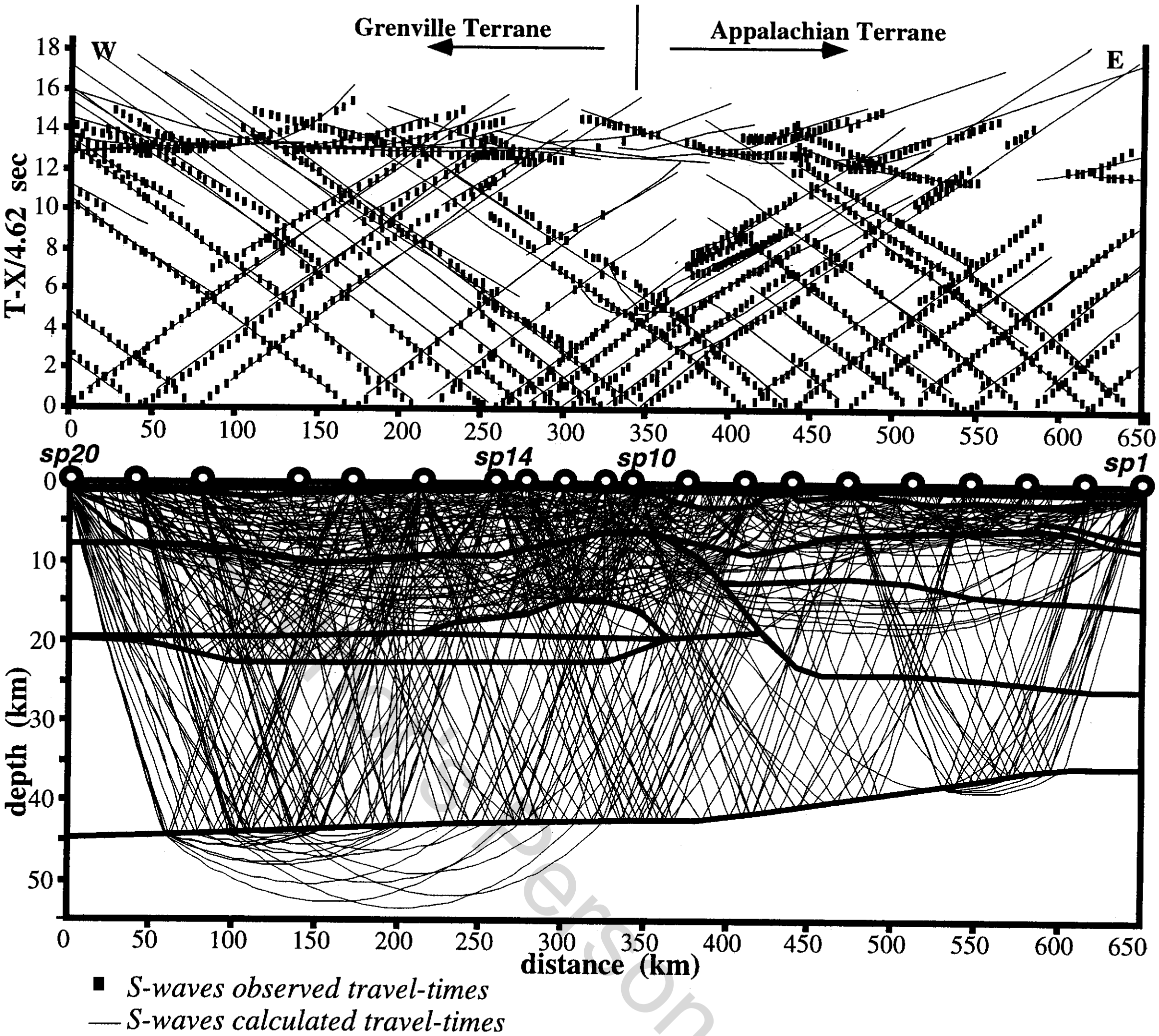

Figure 6. Two-dimensional ray-tracing model for *S* wave phases along the O-NYNEX refraction profile. The high density receiver and source spacing allowed a high ray coverage.

velocity (~3.7 km/s) found beneath the Tahawus Complex and west of the Grenville Ramp is consistent with values obtained from the inversion of teleseismic receiver functions [*Owens*, 1987]. This definitely refutes the idea that the extremely low *S* wave velocity anomaly (~3.4 km/s) found in the lower crust beneath eastern Canada [*Jordan and Frazer*, 1975] is also present here beneath the Grenville Province.

The upper mantle velocity structure is constrained by both *P* and *S* wave refracted arrivals in the Grenville Province. The *S* wave modeling is consistent with the west dipping geometry of the Moho derived by *Hughes and Luetgert* [1991, 1992].

V_P/V_S Ratios

Plate 1c shows the crustal V_P/V_S ratios derived in this study. V_P/V_S cross sections often show more lateral variation than separate V_P and V_S sections. This may be due to higher variability of the V_P/V_S parameter, or it can reflect instability of the V_P/V_S ratio itself, which may be related to different travel paths of *P* and *S* waves. If the smaller-scale (both in amplitude and extent) anomalies (e.g., small-scale lateral variations in V_P/V_S that are observed in the Appalachian upper and middle crust) are not well constrained and may be artifacts, we assert that V_P/V_S anomalies having regional extent or those that can be directly connected to exposed rocks, such as the Marcy Anorthosite, are reliable.

In addition to a general increase with depth, the most outstanding result of V_P/V_S modeling is that Poisson's ratio is distinctly higher in the Proterozoic Grenville Province than in the Phanerozoic Appalachian crust. Moreover, the Grenville and Appalachian Provinces have V_P/V_S ratios that are higher and lower, respectively, than 1.78, the average value proposed for the continental crust by *Zandt and Ammon* [1995].

V_P/V_S ratios (Plate 1c) suggest that the Grenville lower crust extends farther east than the Champlain thrust, into the Appalachian Province and that the Grenville Ramp, separating the autochthonous Grenville Terranes from the accreted Appalachian Terranes, can be extended down to the Moho. The crust exhibits V_P/V_S ratios that range from 1.85 ± 0.02 (Grenville) to less than 1.70 ± 0.02 (Appalachian). The average V_P/V_S ratio for the whole crustal section in the Grenville and Appalachian Provinces differs by 0.1. The modeled V_P/V_S ratios are higher and better constrained than those obtained by *Hughes and Luetgert* [1991], who obtained their estimates by comparing *P* and *S* arrival times from shot point 10 for the Marcy Anorthosite. For the Tahawus Complex

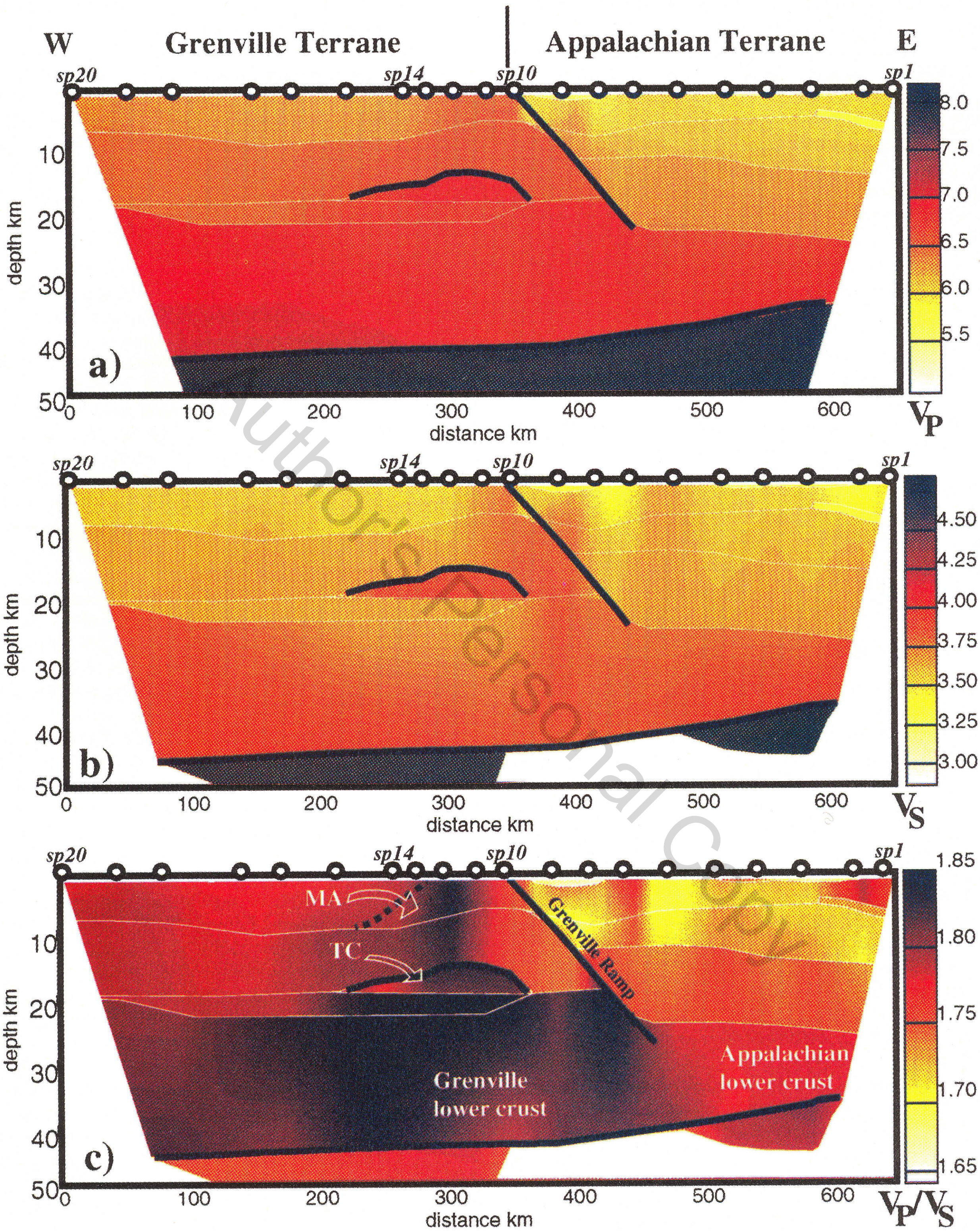

Plate 1. (a) V_P, (b) V_S, (c) V_P/V_S ratios. The combined *P* and *S* wave modeling clearly show that the difference in seismic properties between the Grenville and Appalachian Provinces can be followed at depth down to the Moho. The highest V_P/V_S ratios are found in the Grenville Province and are associated with *P* wave velocities in the range of 6.6-7.0 km/s. M. A., Marcy Anorthosite; T. C., Tahawus Complex.

and for the lower crust they obtained Vp/Vs ratios from the *P* wave velocity, determined by seismic refraction modeling, and the *S* wave velocity, given by previously published teleseismic modeling [*Hughes and Luetgert*, 1992].

We found V_P/V_S ratios greater than 1.77 for the whole Grenville crust, except for the first kilometer of depth between shot points 19 and 15, where V_P/V_S ratios are as low as 1.73. Bodies having V_P/V_S ratios around 1.85 are distributed in the whole Grenville section but are mostly concentrated in the lower crust. On the basis of the V_P/V_S signature alone, a rough subdivision between the present upper (V_P/V_S= 1.80, 0-20 km) and lower (V_P/V_S=1.84, 20-45 km) crust can be made. In the upper crust an anomalous body (V_P/V_S=1.84) is modeled beneath shot points 13-10, where the Marcy Anorthosite is exposed at the surface. At ~20 km depth the Tahawus Complex exhibits an average V_P/V_S ratio of ~1.83. Finally, the 25-km-thick Grenville lower crust has an average V_P/V_S ratio of 1.84, which is consistent with values determined by receiver function inversions [*Zandt and Ammon*, 1995] for Precambrian shields.

The Appalachian crust can be clearly subdivided into upper (average V_P/V_S=1.71), middle (average V_P/V_S=1.74), and lower crust (average V_P/V_S=1.76). These values follow the expected decrease in the amount of quartz-bearing rocks as the depth increases. Values found for the lower crust are consistent with results given by receiver function inversions [*Zandt and Ammon,* 1995] for Paleozoic orogenic belts. V_P/V_S ratios in the upper mantle range between 1.77 and 1.80.

Composition of the Crust

V_P/V_S ratios of the crust can be discussed in terms of fluid pore pressure, fabric, and composition. High V_P/V_S ratios can be related to high pore pressure, attitude of the foliation parallel to the ray path, or low quartz content [*Kern et al.*, 1993; *Hughes et al.*, 1993; *Musacchio*, 1993]. High pore pressure results in a greater decrease of *S* wave velocity than the decrease in *P* wave velocity, hence a high V_P/V_S ratio. In our case, the high V_P/V_S ratios found in the Grenville crust are associated with a relatively high *P* wave velocity (Plates 1a and 1c); therefore, the high ratios are not likely due to high pore pressure. Since rock foliation affects the *P* wave anisotropy and the *S* wave birifrangence, it results in higher V_P/V_S ratios for wave propagation in the foliation plane than for propagation in any other direction. To have any significant influence on the V_P/V_S ratios at the scale of our seismic profile, a constant foliation attitude over hundreds of kilometers is required.

Thus, composition is a good approximation for the high V_P/V_S ratios in the O-NYNEX crustal section. Minerals that exhibit V_P/V_S ratios higher than 1.8 include plagioclase, amphibole, pyroxene, and Fe-olivine. Plagioclase composition has a significant effect on V_P/V_S ratios; an increase of Ca correlates with an increase of the V_P/V_S ratio. Fe substitution for Mg in pyroxene and olivine also increases the V_P/V_S ratio [*Christensen*, 1996]. Thus we expect the highest V_P/V_S ratios to be related to basic compositions.

In Figure 7, data from the literature and laboratory measurements on samples collected in the Adirondack Mountains and in the Appalachian thrust belt are compared with the modeled *P* wave velocities and V_P/V_S ratios. We have distinguished three different fields on the basis of the V_P/V_S ratios. The felsic field refers to rocks in which the intermediate-to-high silica content results in low *P* wave velocity (less than 6.7 km/s) and a low V_P/V_S ratio (less than 1.78). The anorthosite field refers to rocks in which high plagioclase content results in relatively low *P* wave velocity (between 6.6 and 7.1 km/s) and a high V_P/V_S ratio (greater than 1.85). The mafic field refers to rocks in which low silica content results in high *P* wave velocities (higher than 6.7 km/s) and high V_P/V_S ratios (up to 1.86). The upper right corner of the mafic field in Figure 7 corresponds to mafic rocks with a high plagioclase content (i.e., gabbro-norite). We will discuss the composition of the crust from top to bottom, starting with the Grenville Province.

Grenville Province

The Grenville crust exhibits high V_P/V_S ratios and high *P* wave velocities that are indicative of an overall intermediate-to-basic composition. In spite of the known differences in composition between the Central Metasedimentary Belt (supracrustal metasedimentary rocks) and the Central Granulite Terrane (middle to lower crustal meta-igneous rocks with tonalitic to gabbroic composition), no substantial differences in the V_P/V_S signature have been imaged at depth (Plate 1c). The high V_P/V_S ratio (up to 1.84) of the Marcy anorthosite is consistent with its high Ca-plagioclase content and/or pyroxene. The Marcy massif consists of silicic melts (mafic syenites, monzonites, and quartz syenites) cored by anorthositic rocks (anorthosites, gabbros, and norites). As shown in Figure 7, we might expect, depending on the amount of silicic rocks mantling the massif and the chemical composition of the plagioclase, the overall V_P/V_S ratio to be smaller than the ratio for pure anorthositic rock samples. Although there is no unequivocal geophysical evidence indicating the bottom of the massif, seismic reflection images on other anorthosite massifs in the Grenville Province (Morin and Bouchette massifs [*Martignole and Calvert*, 1996]) and gravity modeling [*Simmons*, 1964] suggest that the Marcy massif is no more than 10 km thick (Figure 8).

At midcrustal depths, the Tahawus Complex (Plate 1 and Figure 8) displays *P* wave velocities and V_P/V_S ratios typical of mafic amphibolitic-to-granulitic rocks (Figure 8). The V_P/V_S ratio and previous reflection seismic imaging [*Brown et al.*, 1983; *Klemperer and Calvert*, 1985] indicate that the bottom of the Tahawus Complex is ~25 km deep (Figure 8). On the basis of the seismic reflection image and the electromagnetic response, three different compositions have been suggested for the Tahawus Complex: igneous layering, gneissic layering, and metasedimentary and metavolcanic layering [*Klemperer et al.*, 1985]. The high V_P/V_S ratio of the Tahawus Complex indicates that it is likely to be a gabbroic body, where the high content of Ca-plagioclase, pyroxene, or amphibole minerals accounts for the high V_P/V_S ratio (1.83). In Figure 7, the Tahawus Complex and the Marcy Anorthosite fall into two separate fields, the mafic field and the anorthosite field. The main difference between these two fields is the amount of plagioclase and its chemical composition; samples plotting in the mafic field have less abundant and/or less calcic plagioclase than the anorthositic rocks. Layered massif-type anorthosites (e.g., Duluth Complex, Minnesota; Glen Mountains Complex, Oklahoma) are thought to represent an intermediate member in a complete spectrum from anorthosite massifs to layered mafic intrusions [*Ashwal*, 1993]. We propose that the high V_P/V_S ratio, its reflection signature as a laminated body, and the

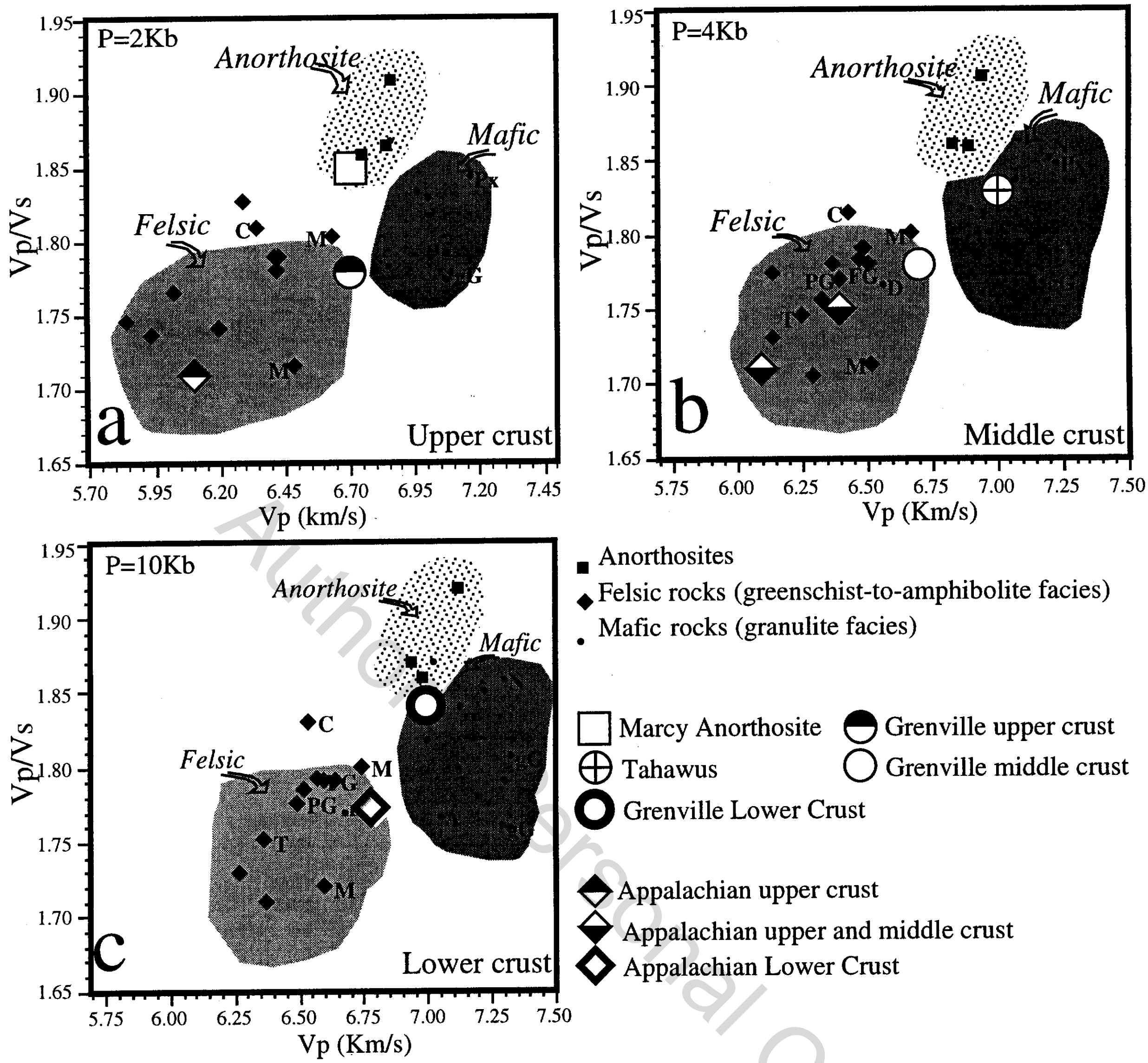

Figure 7. V_P/V_S ratios versus V_P at pressures characteristic for the (a) upper, (b) middle, and (c) lower crust. The temperature correction for the seismic wave velocity is calculated using a geotherm of 15 °C/km [*Blackwell*, 1971]. Solid symbols indicate laboratory measurements on rock samples. Open symbols indicate average values obtained from seismic modeling along the O-NYNEX profile. Shaded areas group rocks having similar composition as well as similar seismic properties: Anorthosite, anorthositic rocks; Mafic, basic rocks (granulite metamorphism); Felsic, intermediate-to-silicic rocks (low- to medium-grade metamorphism). In the mafic rocks field, gabbro granulites are plotted without labels. In the felsic rocks field granitic gneiss, granite-granodiorite, schist and phyllite are plotted without labels. Px, pyroxenite; gG, garnet granulite; N, norite; A, amphibolite; C, charnockite; M, magnerite; PG, paragranulite; T, biotite tonalite gneiss.

high conductivity are consistent with an interpretation of the Tahawus Complex as a layered massif-type anorthosite. Although no measurements on rock samples from the layered massif-type anorthosites are available, we can expect the observed difference in V_P/V_S ratio between the Marcy Anorthosite and the Tahawus Complex to be consistent with less plagioclase in the layered massif-type anorthosites. The seismic lamination of the Tahawus Complex is analogous to that found for layered mafic intrusions such as Bjerkreim (Norway), Stillwater (Montana), Rhum (Scotland), Honningsvag (Norway), and Ivrea (Italy), and is due to reflections from alternating anorthositic (plagioclase-rich) layers and gabbroic (plagioclase-depleted) layers [*Deemer and Hurich*, 1994]. Because of their high content of metal oxides or sulfides, layered massif-type anorthosites can also account for the high conductivity of the Tahawus Complex [*Parkhomenko*, 1982].

In Figure 7c the Grenville lower crust (V_P/V_S =1.84; Vp=7.0 km/s) falls into a field where the abundance of Ca-plagioclase and pyroxene play an important role. It is well known that possible constituents of the lower crust include anorthosites, mafic granulites (gabbros and pyroxenites), and amphibolitic assemblages. Pyroxenites and amphibolites are unlikely to be representative lithologies for the Grenville lower crust; the former exhibit a higher *P* wave velocity (7.9±0.1km/s) and both have a lower V_P/V_S ratio (Table 1; 1.75±0.01 for the pyroxenites and 1.76±0.04 for the amphibolites). Garnet-rich granulitic lithologies (Table 1; V_P/V_S=1.76; V_P=7.3 km/s),

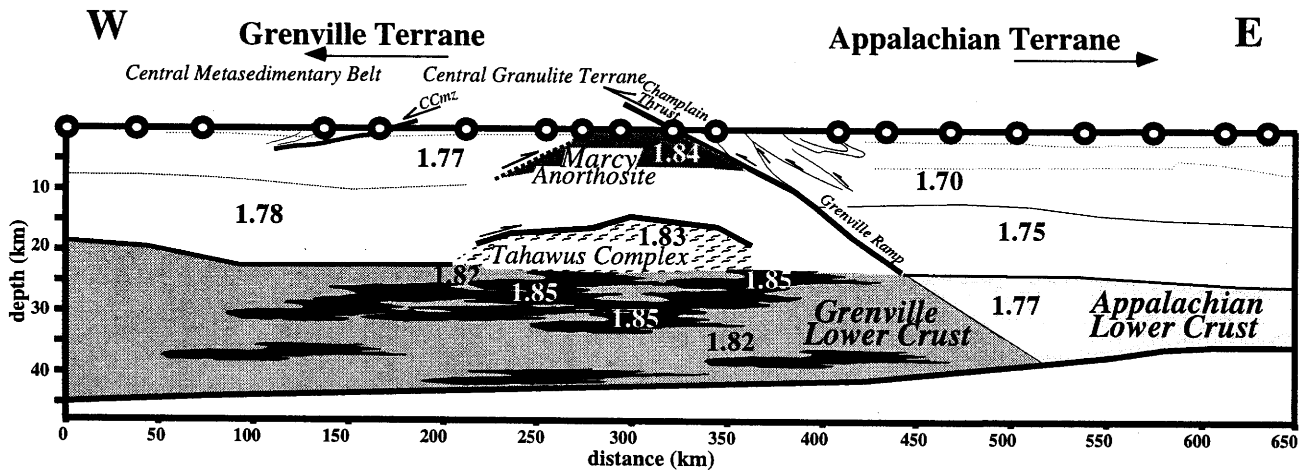

Figure 8. Interpretative cross section of the V_P/V_S ratio image along the O-NYNEX seismic refraction profile. V_P/V_S ratio values are also plotted. Thick lines represent significant seismic boundaries. Thin lines indicate structures derived from the interpretation of COCORP seismic data [i.e., *Ando et al.,* 1984; *Culotta et al.,* 1990]. Darker gray fillings indicate higher V_P/V_S. In the lower crust high V_P/V_S ratios correlated with gabbro-granulite bodies are plotted in black. CCmz, Carthage-Colton mylonite zone. The Marcy Anorthosite, the Tahawus Complex, and the V_P/V_S ratio anomalies located in the lower crust may be related to the mid-Proterozoic magmatism.

Table 1. Laboratory Measured Average *P* Wave Velocities and Vp/Vs Ratios on Rock Samples at Upper (2 kb), Middle (4 kb) and Lower (10 kb) Crustal Pressure

Rock Type	2 kb		4kb		10kb		Ref.
	V_P, km/s	V_P/V_S	V_P, km/s	V_P/V_S	V_P, km/s	V_P/V_S	
Anorthosite*	6.740	1.860	6.832	1.862	6.940	1.870	1
Gabbroic anorthosite granulite*	6.857	1.909	6.946	1.906	7.120	1.920	1
Gabbroic anorthosite granulite(2)*	6.832	1.866	6.887	1.860	6.980	1.860	1
Middle crustal rocks							
Granite-granodiorite			6.296±0.121	1.705±0.043	6.372±0.124	1.710±0.043	2
Granitic gneiss			6.145±0.107	1.730±0.050	6.271±0.101	1.729±0.051	2
Biotite tonalite gneiss			6.256±0.161	1.745±0.075	6.366±0.160	1.751±0.075	2
Quartz mica schist			6.370±0.31	1.780±0.145	6.523±0.324	1.785±0.141	2
Felsic granulite			6.474±0.127	1.783±0.063	6.571±0.131	1.792±0.065	2
Paragranulite			6.402±0.143	1.770±0.062	6.497±0.135	1.776±0.060	2
Charnockite*	6.342	1.810	6.435	1.815	6.540	1.830	1
Quartz magnerite*	6.488	1.715	6.522	1.713	6.600	1.720	1
Magnerite*	6.631	1.804	6.678	1.801	6.750	1.800	1
Garnet gneiss*	6.420	1.780	6.510	1.780	6.640	1.790	1
Biotite gneiss*	6.410	1.790	6.490	1.790	6.600	1.790	1
Phyllitic schist*	6.425	1.790	6.491	1.790			3
Phyllite*	6.192	1.741	6.327	1.756			3
Mica schist*	6.026	1.765	6.142	1.774			3
Granitic gneiss*	6.051	1.593	6.159	1.605			3
Quartzite*	6.061	1.476	6.109	1.483			3
Lower Crustal Rocks							
Mafic granulite			6.902±0.181	1.817±0.036	7.000±0.147	1.818±0.032	2
Amphibolite			6.939±0.199	1.761±0.042	7.046±0.131	1.767±0.044	2
Diorite			6.566±0.144	1.766±0.026	6.675±0.12	1.770±0.031	2
Gabbro-norite-troctolite			7.200±0.255	1.852±0.048	7.299±0.263	1.858±0.051	2
Mafic-garnet-granulite			7.197±0.164	1.796±0.041	7.324±0.154	1.807±0.046	2
Hornblendite			7.222±0.01	1.749±0.007	7.317±0.041	1.759±0.006	2
Pyroxenite			7.812±0.099	1.747±0.066	7.935±0.098	1.756±0.066	2
Gabbroic granulite*	7.064	1.792	7.110	1.791	7.200	1.780	1
Gabbroic granulite(1)*	7.066	1.774	7.166	1.776	7.300	1.790	1
Gabbroic granulite(2)*	6.999	1.831	7.042	1.833	7.130	1.840	1
Almandine granulite*	7.083	1.779	7.175	1.768	7.290	1.760	1
Granulite(2)*	6.954	1.834	7.070	1.836	7.220	1.850	1
Granulite(3)*	6.847	1.784	6.955	1.792	7.120	1.800	1
Metasedimentary granulite*	6.857	1.869	6.898	1.858	7.020	1.870	1
Almandine pyroxenitic gneiss*	7.160	1.844	7.225	1.848	7.320	1.850	1

Standard deviation is included only when given by the author. References: 1, *Manghnani and Ramananantoandro* [1974]; 2, *Christensen* [1996]; 3, this work (new measurements).

*Samples collected in the area of the O-NYNEX profile.

Table 2. *P* Wave Velocities and Vp/Vs Ratios for Crust of Different Ages

Region	Age	Average Crustal V_P, km/s	Average Crustal V_P/V_S	Lower Crustal V_P, km/s	Lower Crustal V_P/V_S	Ref.
Northern Baltic Shield	Archean-early Proterozoic	6.67	1.75	7.30	1.78	4
Southern Baltic Shield	late Proterozoic	6.51	1.79	7.10	1.78	7
Central Baltic Shield	early-Proterozoic	6.50	1.76	7.40	1.77	8
Grenville	mid-late Proterozoic	6.80	1.81	7.00	1.84	1,2
Appalachian	Paleozoic	6.49	1.73	6.80	1.76	1,3
Alpine-Himalayan orogenic belts	Meso-Cenozoic	6.25*	1.71*	6.50	1.75	5,6
Shield	Proterozoic	6.50*	1.84*			6

The standard deviation on Vp measurements ranges from ±0.1 to ±0.2 km/s; Vp/Vs ratios range from ±0.012 to ±0.03. References: 1, this work; 2, *Hughes and Luetgert* [1992]; 3, *Hughes and Luetgert* [1991]; 4, *Walther and Flueh* [1993]; 5, *Musacchio* [1993]; 6, *Zandt and Ammon* [1995]; 7, *Barth and Klemperer* [1993]; 8, *Musacchio et al.* [1995].

*Data from receiver function.

proposed for the Grenville lower crust [*Hughes and Luetgert*, 1992], are not consistent with its high V_P/V_S ratio and relatively low *P* wave velocity (Figure 7). Rather, we favor gabbro granulites (without garnet) as the main constituent of the Grenville lower crust, the anorthitic content of the plagioclase, typical for gabbros at that depth, and the pyroxene justify the measured V_P/V_S ratio (Figure 7).

If we compare V_P/V_S ratios for crust of different age (Table 2) and if we interpret the V_P/V_S ratios in terms of composition, we may infer that the middle-Proterozoic lower crust has an anomalous content of anorthosite-bearing rocks (i.e., gabbro with high plagioclase content). This is consistent with the fact that in the middle-Proterozoic the crust underwent a unique magmatic event related to the emplacement of massif-type anorthosites.. Seismic and geochemical data [*Durrheim and Mooney*, 1991, 1992]. suggest that the Proterozoic crust have been thickened by magmatic underplating [*Durrheim and Mooney*, 1994].

On the basis of the V_P/V_S ratio (Plate 1c) the Grenville lower crust extends farther east than the mapped boundary between the Appalachian and Grenville Provinces (i.e. the Champlain thrust) (Figure 8). This result is consistent with the composition of xenoliths from the Ayre Cliff dike in Quebec which indicates that in the Appalachian Province, mafic assemblages and anorthosite fragments are correlated with the Grenville exposure in the Adirondack Mountains [*Williams and McHone*, 1984; *Trzcienski and Marchildon*, 1989]. The Grenville Ramp has been imaged as a zone of east-dipping structures with a dip of about 25°-30° at depth [*Ando et al.*, 1984]. We interpret these to be made up of thrust sheets of both Grenville and Appalachian Terranes [*Ando et al.*, 1984; *Culotta et al.*, 1990; *Stewart et al.*, 1986]. Since V_P/V_S ratios can only give information on the variation of the overall composition across the ramp, alone it can provide little information on the mode of interaction between the two terrains. On the basis of the V_P/V_S ratios a significant difference exists in the composition of the lower crust of the Grenville and Appalachian Terranes. We attribute this difference to be due to modification of the Grenville lower crust during the emplacement of the anorthosite massifs.

Appalachian Province

The Appalachian Province exhibits a normal increase in V_P/V_S values with depth, an observation that is consistent with the presence of quartz-bearing rocks in the upper crust and an expected decrease of silica content with depth. In Figures 7a and 7b those fields related to the Appalachian upper and middle crust match felsic rocks such as felsic gneiss and intermediate-to-high-grade metapelitic rocks. The upper crustal bodies, such as the Green Mountains, Bronson Hills Anticlinorium, or the White Mountain Batholith are not distinguished by their V_P/V_S ratio. Seismic reflection images show these bodies as having a significant extent, reaching depths of ~10 km and thickness of ~7 km (i.e., the Green Mountain Anticlinorium [*Brown et al.*, 1983; *Ando et al.*, 1984]). Our results are surprising considering that the Green Mountains are slices of Grenville basement [*Stanley and Ratcliffe*, 1985]. The retrograde metamorphism (i.e., the formation of chlorite-muscovite-epidote [*DellaRusso and Stanley*, 1986]) that affected the Green Mountains during the Taconic orogeny may have erased the expected high V_P/V_S ratio and a high *P* wave velocity [*Hughes et al.*, 1993]. The abrupt increase in V_P/V_S ratio associated with an increase in seismic velocity across the midcrustal reflector (Plate 1) delineates an increase in the mafic content of the lower crust (Figure 8). In Figure 7 the Appalachian lower crust plots at the border between the felsic rocks field and the mafic rocks field. We infer a dioritic composition for the Appalachian lower crust and an upper amphibolitic to lower granulitic metamorphic grade.

Conclusions

We have modeled the crustal V_P/V_S ratio along the O-NYNEX seismic refraction profile to investigate the crustal composition of the Proterozoic Grenville Province and the Phanerozoic northern Appalachian Province. The model is constrained by high-quality, densely sampled *S* wave phases recorded along the 650-km-long profile.

Our major conclusions are the following:

1. There is a clear distinction between the Grenville

(average V_P/V_S ratio of ~1.81) and Appalachian (average V_P/V_S ratio of ~1.73) crust. This distinction persists throughout the crust. The eastern edge of the Grenville Province extends 100 km east under the Champlain thrust which is the mapped contact between the Grenville and Appalachian Provinces, and this contact can be followed down to the Moho (Figure 8).

2. The Appalachian crust shows typical continental crust V_P/V_S ratios (1.70-1.77) at all depths. The lower crustal *P* wave velocity (6.7-7.0 km/s) and V_P/V_S ratio (1.77) are indicative of an intermediate-to-basic composition and upper amphibolite to lower granulite metamorphic grade.

3. The Grenville crust, which includes the Marcy Anorthosite within the Adirondack Mountains, shows anomalously high V_P/V_S ratios (1.77-1.85). The Marcy Anorthosite, the mid crustal (20 km) Tahawus Complex, and the 25-km-thick lower crust all have high V_P/V_S ratios (1.82-1.85). The *P* wave velocity (6.9-7.2 km/s) and the V_P/V_S ratio in the lower-crust are indicative of a gabbroic composition.

4. The mid crustal Tahawus Complex likely consists of a large layered massif-type anorthosite intrusion beneath the Marcy Anorthosite, based on its high V_P/V_S ratio, seismic lamination, and high conductivity.

5. Comparison of V_P/V_S ratio versus age, from Archean to Cenozoic, indicates a gradual increase with age up to the middle Proterozoic and a decrease in the early Proterozoic and Archean (Table 2). This suggests that the mid-Proterozoic crust was affected by a magmatic event that changed its average composition into gabbroic-anorthosite. In view of the fact that the V_P/V_S ratios found in the mid-Proterozoic crust have not been found in crust of any other age, the event that produced the anorthosite to gabbroic composition appears to be unique.

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