Point Estimates of Crustal Thickness Using Receiver Function Stacking

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ABSTRACT

Introduction: Through receiver function analysis, this study inquires into some of the most basic properties of the crust below Southern and Central Quebec. **Methods**: This is accomplished, using receiver function technique, by stacking waveforms from 277 teleseismic events magnitude 6.0 and larger to find the delay in arrival time for several phases of the P-wave coda, relative to the initial P-wave arrival. This information is used to establish a linear relationship between thickness and P- to S-wave velocity ratio, each of which is stacked for a given station to identify a best-fit estimate for depth to the Moho and Vp/Vs ratio. To determine their accuracy these results are compared with previous seismic studies, as well as synthetically generated receiver function P-wave arrivals based on simple 1D crustal models. Thickness calculations for the crust varied from 28 to 48 km; variation which was most likely the result of either complicated 3D structures or a shortage of available high-magnitude events for some stations. Most of the results fell within appropriate windows outlined by studies like LITHOPROBE. **Discussion**: Given that the 9 broadband stations used in this study compose an area from the Superior Province, Grenville Province and a selection of their subprovinces and intrusions, reliable evaluations of the crustal thicknesses below these seismic stations have broad relevance in understanding the crustal structure below Quebec.

KEYWORDS

Seismology: Study of waves of energy released by an earthquake (seismic event).
Receiver Function: Deconvolution of a three-component seismogram into one single file.
LITHOPROBE: Series of reflection seismology transects performed to characterize structure of crust in targeted areas across Canada.
Abitibi: Neoarchaean greenstone belt on Canadian Shield.

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INTRODUCTION

This project used seismograms recorded at a number of Quebec seismic stations, all of which are part of the Canadian National Seismic Network. These stations were set up in Belleterre (BELQ), Chibougamau (CHGQ), Dolbeau (DMCQ), La Tuque (LATQ), Lebel-sur-Quévillon (LSQQ), Matagami (MATQ), Nemaska/Némiscau (NEMQ/NMSQ), and Rénard Mine (YOSQ) as shown in Fig. 1. They overlie several interesting geological provinces in the region, covering orogenic and accretionary events dating as far back as the Neo- or Mesoarchaean (approximately 2.7Ga). Estimates of crustal thickness below these stations are useful in characterizing the 'topography' of the crust-mantle interface, enhancing our understanding of how ancient tectonic events continue to shape and define the structure of our continent.

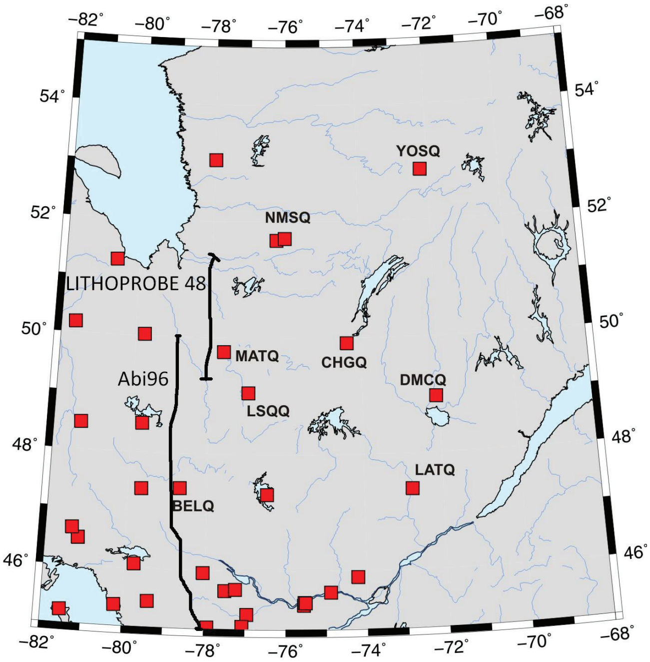

Fig 1. Map of study area with seismic stations indicated by red squares. Stations used in study are labelled. Approximate locations are shown for LITHOPROBE transect 48 and Abi96 line.

The Abitibi Greenstone belt, where MATQ, LSQQ, CHGQ, and BELQ stations are located, is in the Superior Province. It is a supracrustal Archaean belt composed of low-grade, regionally metamorphosed igneous and sedimentary rocks, which are mostly of mafic origin (as supported by the high Vp/Vs ratios for this region *(1)*. The term "greenstone" reflects the presence of the green minerals chlorite and actinolite. In 2007 it was determined that portions of the Abitibi are highly anisotropic: the minerals therein favour certain directions of wave propagation over others, resulting in differing wave travel times depending upon the incoming angle of the ray and the orientation of the station *(1)*. Crustal thickness estimations in past studies conducted in the Abitibi, along LITHOPROBE transect 48 using seismic reflection profiles *(2)*, did not exceed 40 km. The depth below the other seismic reflection line, Abi96 above 46.6oN, varied between 35 and 40 km according to a study conducted by Rondenay et al *(3)*. Both of these works involved interpreting reflected seismic profiles by picking out key reflectors in the earth's crust and connecting them into coherent layers. The current work, however, assumes a homogeneous single layer crust where the only seismic reflector to alter wave speed will be the Moho. Therefore the amount of complexity that can be perceived by reflection seismology depends on the interpreter, whereas in this refraction study there is little to no complexity assumed.

The YOSQ Station is contained in the Opinaca gneissic belt of the Superior Province, while NMSQ and NEMQ are in the 2850 Ma plutonic Opatica belt. The Superior is the world's largest Archaean craton. Due to lack of seismic station coverage it has not previously been given a crustal thickness estimate.

Both LATQ and DMCQ are in the Grenville Province, part of the Grenville Orogeny that continues from eastern Canada into the central United States. It is a relic of a Himalayan-type continent-continent collision that occurred around 1 billion years ago following 800 million years of convergence at the southeast corner of the proto-continent Laurentia *(2)*. Despite a lack of remaining mountainous terrain, there is a great deal of relic relief at the crust-mantle interface. Eaton et al. (4) published an estimate of crustal thickness in a further western part of the Grenville Province of between 34-52.4 km, while in 2000 Ludden and Hynes *(2)* published a narrower range of between 40 km in the north and 45 km in the south, on a line about 100 km southwest of LATQ.

METHODS

This study uses the method of Zhu and Kanamori *(5)*, stacking receiver functions (RFs) and comparing arrival times of P-wave transformations with the arrival of the initial P-wave. Receiver functions are created by deconvolving the vertical component from the radial (along path) and tangential components (at 90o to the direction of propagation) of a seismogram for a particular earthquake. Effectively, it turns three different axes of motion from each event into just one seismogram so one can more easily investigate several earthquakes at once. In particular, using RFs makes it easier to identify the incoming P-wave to S-wave conversions like Ps, PpPs, and the combined PpSs+PsPs, all of which involve conversions of seismic P- and S- waves as they interact with the crust-mantle boundary.

By comparing the difference in arrival times between any of these converted phases and the initial P-wave, we can determine the amount of time it takes a certain type of wave to traverse the thickness of the crust. With this information, the velocity and distance travelled can then be determined using a linear relationship. By utilizing this relationship in conjunction with a range of standardized wave speeds and possible crustal thicknesses, a line in thickness ('H'), versus Vp/Vs ratio ('k'), space can be determined for each conversion arrival (see Fig. 2). When the linear relationships between all three arrivals for each earthquake are combined, the point of intersection indicates the unique solution to the three lines; this represents the best-fit thickness and wave-speed for the crust below that station.

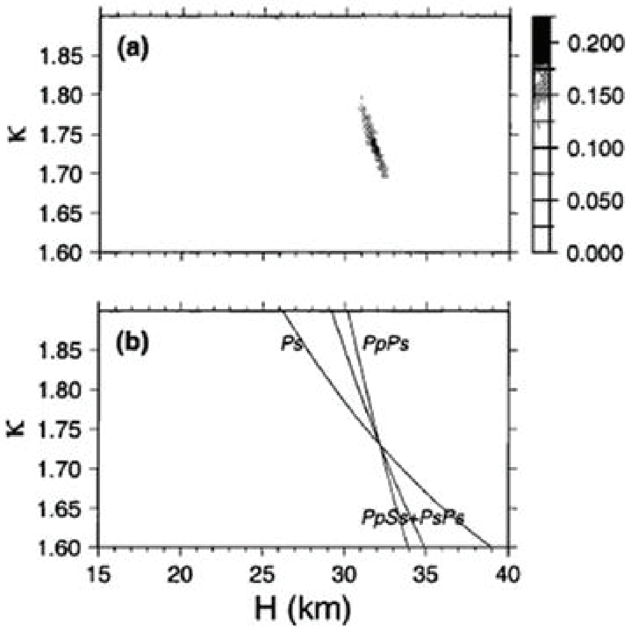

Fig 2. Taken from Zhu and Kanamori *(5)*, this image shows how a single seismic event can be used to pinpoint a best-fit estimate of crustal thickness below the receiver using the relationship between the speed of the wave, the distance it travels, and how fast it travels that distance.

Many earthquakes were used simultaneously for each station by employing a script created by Helffrich *(6)* to stack all of the RFs. This script uses standard vales - depths between 20 km and 50 km, velocity ratios between 1.5 and 2.0, and an assumed P-wave velocity of 6.5 km/s. Because this method compares arrivals of the P-wave coda to the initial P-wave arrival it is robust to different P-wave velocities, meaning that the results should not vary greatly for different assumed P-wave speeds. According to Zhu and Kanamori *(5)*, the estimates provided are sufficiently accurate for approximately a 10 km radius cone beneath the station.

Only large teleseismic earthquakes, meaning earthquakes that occurred between 30 and 90 degrees from an average location between all of the stations (49.859689, -75.223378) with magnitude greater than 6.0, were used for this study. The magnitude had to be adequately high in order to ensure a large signal to noise ratio, as shown in Fig. 3. The spatial constraints on this search were to ensure a steep incidence angle on the incoming ray path, which maximized incoming wave energy, allowed for the transmission of S-waves, and minimized disruptions due to lateral inconsistencies and vertical velocity contrasts.

The RF stacking code *(6)* was used on each station to identify a thickness estimate, all of which are compiled in Fig 4. Note that because NEMQ and NMSQ are in such close proximity to one another and do not overlap in time they were run as one station (NEMQ/NMSQ).

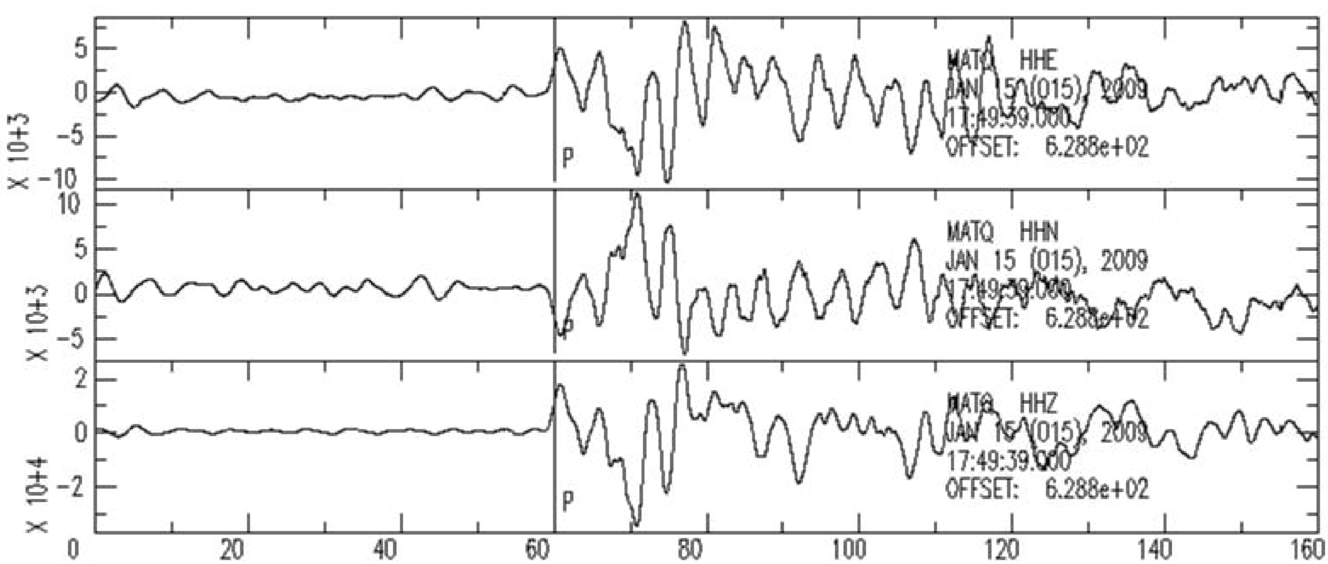

Fig 3. Sample of a "GOOD" seismogram from MATQ station (January 15th, 2009, at 5:49:39PM). A high signal to noise ratio makes identification of the incoming conversions easy to spot.

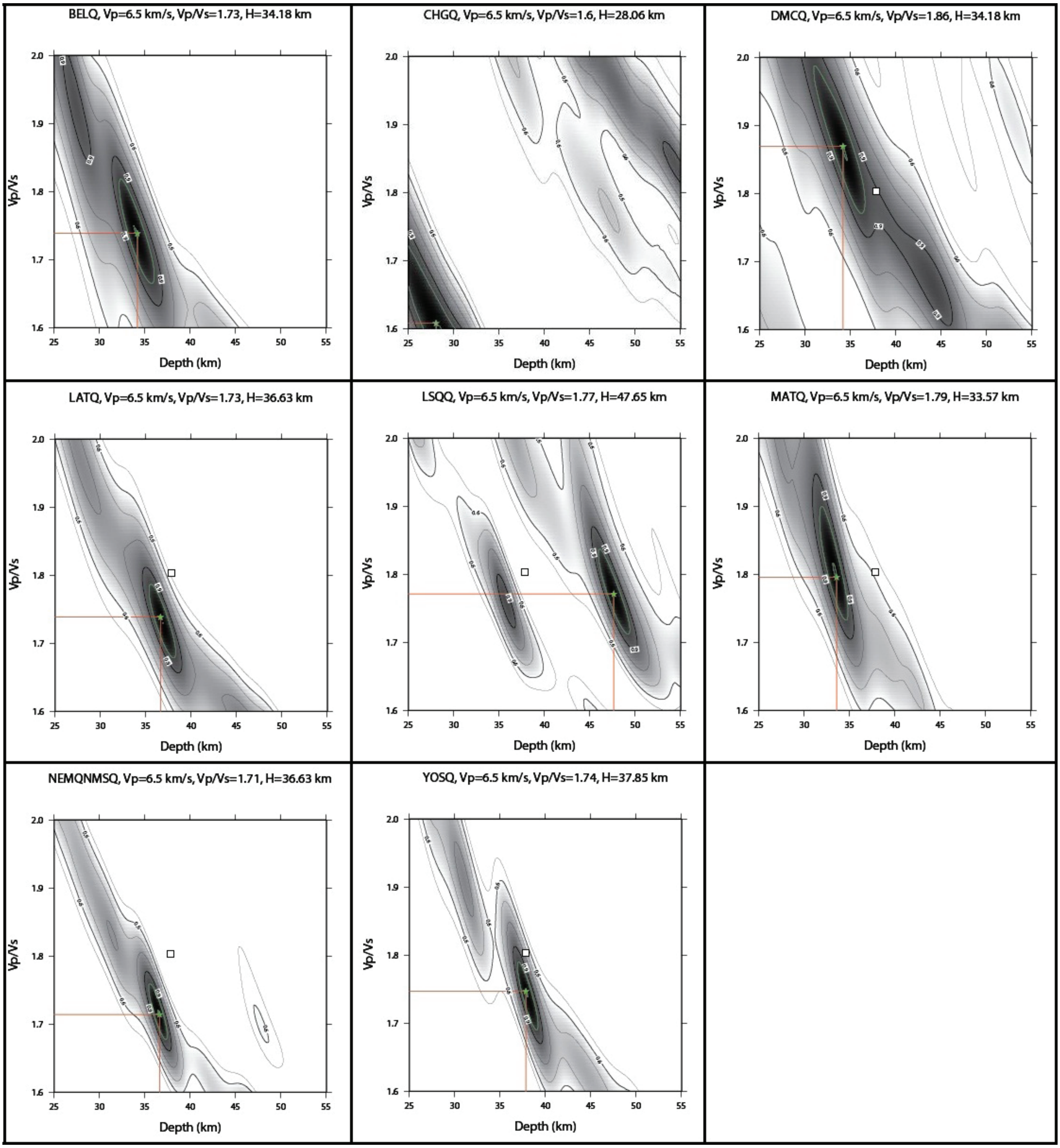

Fig 4. Plots created for each station using code by George Helffrich (6). Best-fit thickness identified for the stacked receiver functions.

RESULTS

In order to test the validity of the RF stacking results they were compared to available previous estimates and to synthetic receiver functions created using code by Helffrich *(6)*. These were prepared for several crustal parameters, including (but not limited to): thickness, Poisson's ratio, and slowness of rays. The Ps arrival times were calculated for receiver functions of synthetic seismograms arriving in crust with thickness ranging from 25 to 50 km, as shown on Fig 5. Five sample events were then taken from each station and Ps arrival time was manually identified. Using this arrival time and interpolating between the different synthetic arrival times, an estimate was made for the crustal thickness (Fig 6), which could be compared directly to the value calculated using the RF stack. This comparison illustrates how well the actual station may fit with a simple 1D, homogenous, anisotropic crust.

The BELQ seismic station is located near Abi96 which used reflection seismology to measure a crustal depth of about 35 km *(3)*. This is similar to the value obtained using receiver functions - a depth of 34.18 km (Fig 4). The synthetic estimate for thickness at this location was slightly lower, at 30 km.

CHGQ showed a very small thickness value of 28.06 km in RF stack (Fig 4). It seems that a more thorough investigation of this area might render slightly different results, given that the expected values from the LITHOPROBE lines are between 35 and 40 km *(2)*, and the synthetic estimate predicts a value closer to 34 km.

The DMCQ thickness estimate of 34.18 km (Fig 4) is less than predicted by both previous work and synthetics, given the estimates made by Ludden and Hynes *(2)*. They anticipated a thickness of the crust in the western Grenville province to be between 40 and 45 km, while the synthetic receiver functions indicated a 39 km thick crust (Fig 6). This particular station lies within an intrusion, which could be why it has such a high Vp/Vs ratio, 1.86, compared to that of LATQ, which also lies within the Central Granulite Terrain of the Grenville Province.

The RF stack value for thickness at La Tuque (LATQ) is 36.63 km (Fig 4), which corresponds well to the synthetic estimate of 36 km (Fig 6). This H-value is slightly lower than anticipated, based on the work of Ludden and Hynes *(2)*, though not inconsistent with the estimates of Eaton et al *(4)*. The Vp/Vs ratio, 1.73, is still high, though, as was suggested by the same paper.

Because LSQQ is located within the Abitibi Greenstone Belt thickness was expected between 35 and 40km *(3)*. The calculated value, 47.65 km (Fig 4), is much thicker. However, there appears to be two areas of best-fit on the plot with similar Vp/

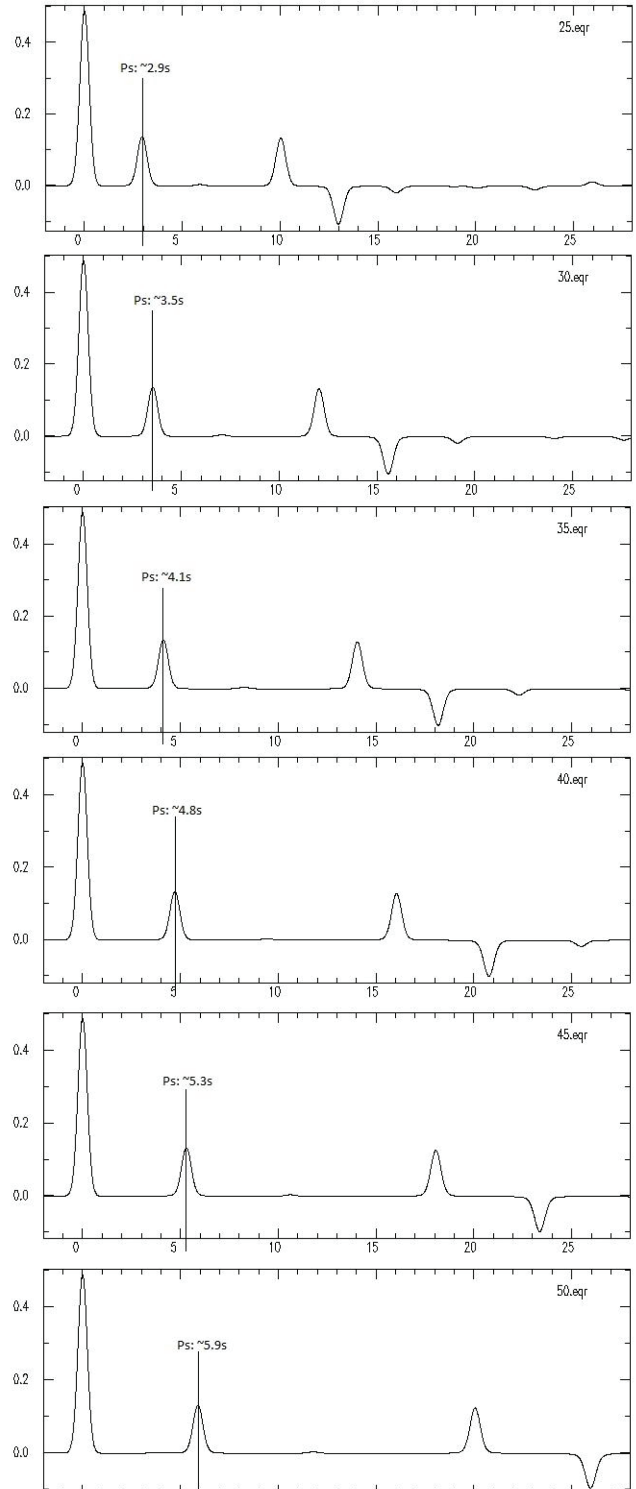

Fig 5. Synthetic receiver functions created for different crustal thicknesses to simply model how arrival time varies with crustal thickness. 25 km: 2.9 s, 30 km: 3.5 s, 35 km: 4.1 s, 40 km: 4.8 s, 45 km: 5.3 s, 50 km: 5.9 s.

Station Name	Avg Ps arrival for 5 samples (s)	Corresponding Synthetic Thickness (km)	Expected Arrival Time (s)	Stacked Thickness Estimate (km)
BELQ	3.5	30	3.98	34
CHGQ	4.02	34	3.26	28
DMCQ	4.7	39	3.98	34
LATQ	4.27	36	4.38	37
LSQQ	4.38	37	5.66	48
MATQ	3.86	33	3.98	34
NEMQNMSQ	4.4	37	4.38	37
YOSQ	4.42	37	4.52	38

Fig 6. Table of values for thickness and Ps arrival time for each station. Synthetic Thickness is calculated by comparing PS arrival times of 5 sample events to the synthetically created RF's. Stacked Thickness was found using the Zhu and Kanamori *(5)* method.

Vs values. Upon consideration of the synthetic value (Fig 6), it is possible that the other solution, 36 km, fits better with the data set.

MATQ station is located near LITHOPROBE A-G transect 48 *(2)*. It was suggested by Ludden that the transect contains a deep, inactive fault which remains from an ancient subduction zone and has an average crustal depth of about 35km. This corresponds well to the values obtained in this study, of 33.57 km for the RF stack and 33 km for the syntheticsn (Figs 4 and 6, respectively).

The Opatica Plutonic Belt – parts of which were interpreted by LITHOPROBE *(2)* – is believed to be a magmatic arc accreted onto the Superior Proto-Craton. It was then underthrust by the Abitibi, resulting in a broad, north-dipping synform in the crust. Similar to the results from MATQ, there may be relicts of an ancient subduction zone here. The values calculated for NEMQ/NMSQ, 36.63 km stacked and 37 km synthetically (Figs 4 and 6, respectively), match nicely with the range predicted by Ludden and Hynes *(2)*.

Located within the understudied Superior Province, no estimate was available for YOSQ. The value calculated here, 37.85 km (Fig 4), therefore cannot be tested against previous work. However, it does match nicely with the synthetically estimated value of 37 km (Fig 6).

DISCUSSION

The limitations of the receiver function stacking method are similar to those of the synthetic estimates. Both procedures assume that the crust of the earth can be modelled as a homogenous 1-dimensional layer sitting on top of the mantle. By placing one value to the entire crust, they negate the effect of anisotropic minerals, relic structures such as subduction zones and imbricate stacks, discontinuous layers, and all manner of heterogeneity. It is likely that in the future more detailed models which account for layers with velocity contrasts will yield more accurate results. In the interim, it is possible to make some preliminary conjectures about the depth to the crust-mantle boundary in southern-central Quebec.

For many stations, there is an approximate correlation between previous studies, stacked values, and synthetically modelled estimates. It is reasonable to assume that this means that the structure below these stations – Belleterre, La Tuque, Matagami, and Nemaska/Némiscau– is fairly uniform and lacks strong vertical structures. In stations such as CHGQ, DMCQ, LSQQ, and YOSQ we see secondary peaks in the RF stacks, which most likely indicate dipping structures. This hypothesis could be tested in future studies by breaking down analysis by back-azimuth to see if thicker and thinner estimates are coming from opposite sides of the station. For locations, such as Dolbeau and Lebel-sur-Quévillon with their anomalously high thickness estimates, further work must be done and additional data obtained to confidently ascertain the crustal thickness.

CHGQ presents the most indeterminate result of all. Upon closer inspection of the later phases, PpPs, PsPs, and PpSs, it is evident that the arrival time varies drastically as a function of incoming direction (back-azimuth). This may be the result of a lateral heterogeneity in the crust, multiple layers, or a steeply dipping structure below Chibougamau. Nonetheless, it is evident that simple 1D modelling of this area will not yield relevant and acceptable results, despite the tempting match between the synthetic estimation and LITHOPROBE results *(2)*. Further studies into the anisotropy of the area may help characterise this idiosyncrasy.

The Vp/Vs ratios can be used to identify the general composition of the crust beneath the stations. While it may seem that the majority of the crust would be polarized between a predominantly felsic bulk composition and the mafic Abitibi greenstone, we see that there is a broad distribution ranging between 1.6, which is very felsic, and 1.86 which is relatively more mafic. The highest value, 1.86, was not found in the Abitibi at all, whereas the 1.6 value was. This suggests that either the Vp/Vs ratio is affected by more than just mafic/felsic composition, or our Vp/Vs estimations are not accurate enough at this time to fully predict the behaviour that we can observe through field observations.

CONCLUSION

This study estimated the Moho depth at 9 seismic stations in Southern and Central Quebec. Overall the values obtained here match with both previous estimates and synthetically generated seismograms, varying between about 28 and 48km. There were problems in matching at stations where either enough data was not available at the time of study, or complicated deep crustal structures preclude model accuracy. For these sites – CHGQ and LSQQ – future work may reveal dipping structures or heterogeneities within the crust.

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