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Piero Poli, Helle Pedersen, Michel Campillo

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1 **Emergence of body waves from cross-correlation of short period seismic noise**

2 P. Poli<sup>1</sup>, H. A. Pedersen<sup>1</sup>, M. Campillo<sup>1</sup>, and the POLENET/LAPNET Working  
3 Group

4 *1-ISTerre, CNRS, universite' Joseph-Fourier, BP 53, 38041 Grenoble cedex 9, France*

5 **SUMMARY**

6 Ambient noise correlation is now widely used in seismology to obtain the surface  
7 waves part of the Green's function. More difficult is the extraction of body waves from noise  
8 correlations. Using 42 temporary broad-band three components stations located on the  
9 northern part of fennoscandian region, we identify high frequency (0.5-2 Hz) body waves  
10 emerging from noise correlations for inter-station distances up to 550 km. The comparison of  
11 the noise correlations with earthquake data confirm that the observed waves can be  
12 interpreted as P and S waves reflected from the Moho. Because the crustal model of the area  
13 is well known, we also compared the noise correlations with synthetic seismograms, and  
14 found an excellent agreement between the travel times of all the observed phases. Polarization  
15 analysis provide a further arguments to confirm the observation of body waves.

16 **Key words:** Interferometry, Body waves, Wave propagation.

17 **INTRODUCTION**

18 The possible extraction of the Green's function through correlation of seismic noise  
19 has opened up for potentially new and exciting developments in seismic imaging and  
20 monitoring of the elastic properties in the Earth. The feasibility of the method is now  
21 understood through a series of theoretical developments (e.g. Weaver and Lobkis, 2001;  
22 Wapenaar, 2004; Roux et al. 2005b, Gouédard et al., 2008, De Verdière, 2011) and through

23 laboratory experiments (Weaver and Lobkis, 2001). Shapiro and Campillo demonstrated the  
24 feasibility of the method by extracting intermediate and long period surface waves on field  
25 data (Shapiro and Campillo, 2004), and numerous studies have now based imaging on the  
26 analysis of seismic surface waves extracted by noise correlations (e.g. Sabra et al., 2005b;  
27 Shapiro et al., 2005; Yang et al., 2007; Yao et al., 2008, Ritzwoller et al., 2011).

28         It is generally assumed that noise is related to surface activity, ranging from human  
29 activity at high frequency to the forcing of oceans and atmosphere at low frequency. In the  
30 absence of deep sources, and with uneven distribution of surface sources, the reconstruction  
31 of body waves relies on the energy that has been scattered at depth. Although with an energy  
32 smaller than the one of the surface waves locally radiated by the sources, the scattered body  
33 waves are present in actual seismograms acquired at the surface, as a part of the almost  
34 equipartitioned diffuse field observed for long lapse time (e.g Hennino et al., 2001, Campillo,  
35 2006).

36         There should therefore be substantial hope of extracting the body wave part of the  
37 Green's function, albeit with a lower signal to noise ratio than the dominant surface waves.  
38 Body waves have indeed been reported from short distance range correlations. Roux (2005a)  
39 identified direct P waves from noise correlation, using data from a small array in California.  
40 Their noise derived P waves were linearly polarized, and with a velocity compatible with a  
41 known velocity model of the area. Draganov et al. (2009) used data from oil exploration to  
42 extract reflected P waves from shallow interfaces. Their observed body waves were in good  
43 agreement with the active source reflection response in the same area. Zhan et al. (2010)  
44 identified S reflected phases from the Moho interface at the critical distance in two shield  
45 areas. The S waves presented a striking agreement with earthquake data. On the contrary, the  
46 extraction of body waves over broader distance ranges has so far not been successful, even  
47 though such waves would be key for body wave tomography at crustal scale.

48 To study the possibility of recovering body waves over large distance ranges from seismic  
49 noise correlation, we processed one year of data acquired at POLENET/LAPNET  
50 seismological array (Kozlovskaya et al., 2006). This dataset is acquired by a seismic array  
51 including 42 broadband stations. The study area is part of the Precambrian northwestern  
52 segment of the East European Craton, and the crust is relatively well known from active  
53 seismic experiments (HUKKA, FIRE, FIRE4, POLAR), from which is it known that the  
54 velocity structure remains relatively simple and with limited lateral variations and a limited  
55 variation of Moho depth (Janik et al., 2007, and reference therein). The major seismic phases  
56 observed from active source experiments were PmP and SmS (Janik et al., 2007), while weak  
57 amplitudes were reported for mantle phases (Pn and Sn) and inter-crustal reflection (Pg and  
58 Sg). As body waves are expected to be strong and impulsive in a crust characterised by weak  
59 scattering and attenuation, the geological and such observations of strong PmP combined with  
60 weak crustal scattering and attenuation (Pedersen et al., 1991, Uski et al. 1996), are  
61 particularly promising elements for the extraction of body waves from noise correlations.

62 We firstly present the dataset and the data processing, after which we discuss the noise  
63 correlations and the fast travelling waves that we interpret as bodywaves. This interpretation  
64 is supported by records of local seismic events, and by numerical simulations (arrival times,  
65 polarization) in a crustal model which is derived from the results of the active seismic studies.

## 66 **DATA AND SIGNAL PROCESSING**

67 We analyse three component seismic data continuously recorded during the  
68 POLENET/LAPNET temporary experiment. We used only stations equipped with broadband  
69 sensors, and included several permanent broadband stations in our data-set. The array  
70 configuration (fig. 1) is approximately a 2D grid with station separations that span from ~50  
71 km to ~600 km. The array was installed between spring and autumn 2007, for a duration of  
72 two years. We used records for the calendar year 2008 during which the array was fully

73 operational.

74 Pedersen et al. 2007 reported the presence of strong directivity of the noise field,  
75 especially observed from strong asymmetric surface waves signals on the noise correlations at  
76 intermediate frequencies (0.02-0.1 Hz) while the high frequency (0.1-1 Hz) part of the noise  
77 was distributed over larger azimuth ranges. Their study was limited to winter month, and the  
78 major part of high frequency energy was related with the sea activity along the eastern  
79 Atlantic coast. In our case, where the seismic array was installed for two years, the average of  
80 the correlations over one year (2008) in a frequency range from 0.1 and 2 Hz present an high  
81 signal to noise ratio over long distances (~ 600 km) and in both causal and acausal parts of the  
82 correlations as expected in a fully diffuse wave-field or in presence of randomly distributed  
83 sources.

84 The standard pre-processing included removing the data mean and trend, prefiltering,  
85 resampling to identical sampling rate and deconvolution of the instrumental responses. The  
86 noise correlations were calculated for all combinations of radial, transverse and vertical  
87 components, which required rotation of the horizontal components for each station pair  
88 according to the azimuth at each station of the great-circle between the two stations. To  
89 analyse broadband signals while removing the effects of earthquakes, we applied two  
90 supplementary steps before correlation. We firstly split the continuous data into four hour  
91 windows and removed the ones where amplitudes were present which were larger than 3  
92 times the standard deviation of the signal. This step additionally reduces the effect of  
93 instrumental problems such as spikes. Secondly, we apply a spectral whitening in a frequency  
94 band from 0.1 to 2 Hz. This second step also diminishes the relative predominant contribution  
95 of surface waves related to the secondary microseismic peak at ~ 0.14 Hz.

96 After this processing the seismic noise traces are correlated for all couple of stations  
97 and stacked over one year, without applying 1-bit normalization. We verified the quality of

98 the correlations by comparing different processing procedures, including one where all major  
99 earthquakes were removed. In this test we used the correlations processed as described above.  
100 Then, using the earthquakes and explosions database of the Finnish seismological service, we  
101 removed all the time windows where earthquakes or explosions occurred and we stacked the  
102 correlations over one year. Since we study high frequency noise data (0.1-2 Hz), local  
103 seismicity can dramatically reduce the quality of the noise correlations (Bensen et al., 2007).  
104 We compared the correlations stack with and without local seismic events and we observed a  
105 stable reconstruction of all the seismic phases. From this observation we consider our  
106 processing procedure as sound and not significantly contaminated by quarry blasts and  
107 seismic events.

108 The bandpass filtered (0.5-2 Hz) noise correlations that have a signal to noise ratio  
109 larger than five are show in Figures 2, 3 and 4. The correlations are organized so that positive  
110 times correspond to waves propagating from the easternmost to the westernmost of the two  
111 stations. Out of the nine components of the correlations, we show the vertical-vertical (ZZ),  
112 radial-radial (RR) and transverse-transverse (TT) components, plotted as a function of the  
113 inter-station distance.

## 114 **RESULTS AND DISCUSSION**

115 In all the analysed components of the correlations we can identify coherent surface  
116 waves propagating from one station to another. The fundamental mode Rayleigh waves (Rg)  
117 portion of the estimated Green's function (EGF) are observed on both ZZ and RR correlation  
118 (fig. 2 and 3 respectively), with a propagation velocity of approximately 3 km/s. On the TT  
119 component (fig. 4) of the EGF we observe fundamental mode Love waves (L), with a velocity  
120 of  $\sim 3.5$  km/s. Both Love and Rayleigh waves appear symmetrically on the seismic sections,  
121 which indicates either a good diffusivity of the noise-field or well distributed noise sources.  
122 The signal to noise ratio of these high-frequency surface waves remains high out to the full

123 distance range covered by the array, i.e. over up to 600 km.

124 We here wish to draw attention to other coherent phases that are clearly present in the  
125 seismic sections. Firstly, we note the coherent phase which is present on the ZZ components  
126 of the correlations (fig. 2) with an apparent velocity of approximately 3.5 km/s, which  
127 corresponds to expected apparent velocities for SmS waves, i.e. waves reflected at the Moho.  
128 These waves are stronger on the acausal part of the correlations, so they must originate in a  
129 different source or scatter distribution than the fundamental mode surface waves discussed  
130 above. This type of wave is not observed on the TT component, however such waves would  
131 be masked by the Love waves which also have velocities close to 3.5 km/s. Secondly, a signal  
132 with an apparent velocity of approximately 6 km/s, i.e. close to the expected apparent velocity  
133 of the PmP phase, is observed on the acausal part of the RR component. Frequency-time  
134 analysis shows that these two phases are non-dispersive over the frequency interval where  
135 they can be observed, which is 0.5-2 Hz. We can therefore, at this stage, hypothesize that  
136 these waves present in the noise correlations are body waves, and most likely SmS and PmP  
137 waves.

138 A first verification of whether the high velocity signals on the correlations are  
139 consistent with being body waves, we compare the noise correlations with earthquake data.  
140 We use the acausal part of the correlation traces of which we use only the ones with a signal  
141 to noise ratio higher than ten (in the body wave arrival windows). We choose a shallow local  
142 event ( $M_L=2.9$ ) located beneath the northern part of the array (fig. 1) and for which clear  
143 signals are observed for the frequency band of interest (0.5-2 Hz). The earthquake data are  
144 preprocessed identically of the continuous noise recordings, and the horizontal components  
145 are rotated to obtain the radial and transverse components.

146 Figure 5 shows the seismic sections with the radial (5a, 5b) and vertical (5c, 5d)  
147 components of the noise correlations (blue) and earthquake records (black). The distance axis

148 corresponds to the inter-station distance for the noise correlations and the epicentral distance  
149 for the earthquake records. The earthquake data clearly show the fundamental mode Rayleigh  
150 waves on both radial and vertical components and the faster P and S wave on the radial and  
151 vertical components respectively. For the earthquake data, both single SmS and PmP are  
152 emerging from a distance of approximately 110km, which corresponds to approximately  
153 critical distance, however their amplitude is high from approximately 200km distance. SmS<sup>2</sup>  
154 is clearly observed from 280 km distance.

155         The comparison with earthquake data seems to give further evidence that the observed  
156 waves that arrive prior to the surface waves could indeed be body waves. Because the crustal  
157 model of the area is well known, and as the crustal model only varies very moderately  
158 beneath the study area, we can also directly compare the noise correlations with the numerical  
159 Green's functions calculated using a 1-D Earth model. We base our velocity model (see table  
160 1) on the interpretation of HUKKA seismic reflection profiles as presented by Janik et al.  
161 (2007). The velocities of the upper crust are modified using the parameters obtained by  
162 Pedersen and Campillo (1991) who analysed high frequency Rayleigh waves from a quarry  
163 blast to obtain shear velocities and quality factor Q down to 3km depth. At larger depths we  
164 used Q values based on Uski et al. 1996. We calculate synthetic seismograms using the  
165 frequency-wavenumber method by Bouchon (1981), using a vertical point source located at  
166 the Earth's surface. The vertical and radial component seismograms, calculated at a 100  
167 points at 10km distance interval, correspond to the Green's function  $G_{ZZ}$  and  $G_{RR}$  which we  
168 need to compare to the Z-Z and R-R correlations.

169         The vertical and radial components of the correlations (blue) and synthetic  
170 seismograms (black) are shown in Figure 6. All the signals are filtered in the frequency range  
171 0.5 to 1 Hz. The synthetic seismograms show dominant fundamental mode Rayleigh waves  
172 on the vertical component, as observed on the Z-Z correlations. The regularly spaced



173 synthetic vertical component seismograms clearly show the single and multiply Moho  
174 reflected S waves beyond the critical distance of  $\sim 110$  km of SmS and up to distances of  
175 350km. The velocity is similar to the one of the early waves in the Z-Z noise correlations, and  
176 the similarity is striking as to the pattern where the SmS<sup>2</sup> phase gradually become dominant  
177 over the SmS phase from 350km and beyond. Weak P waves can also be observed on the  
178 vertical component synthetic seismograms, with a velocity of approximately 6 km/s, as the  
179 ones observed on the Z-Z correlations. The signal to noise ratio on the correlations is however  
180 insufficient to easily detect them over the whole of the section. More evident are the P waves,  
181 observed on the RR correlations, that propagate with a velocity of  $\sim 6$  km/s which is close to  
182 the velocity of the PmP phases observed on the RR synthetics seismograms.

183         The very successful comparison of the noise correlation sections with the earthquake  
184 records and the synthetic seismograms are strong arguments in favor of explaining the early  
185 arrivals in the noise correlations as body waves. A final argument resides in a strong  
186 similarity in polarizations of synthetic seismograms and noise correlations. The analysis of  
187 polarized seismic waves requires phase and amplitude informations of the seismic traces.  
188 Strong non linear pre-processing (as applied for noise correlation) can be a limitation, because  
189 their effect on the amplitude of the signals. Recent results (Cupillard et al., 2011, Prieto et al.,  
190 2011) demonstrate that standard pre-processing as one-bit or whitening have little effect on  
191 the amplitude informations of the noise correlation functions, so that attenuation can be  
192 obtained from the EGF (Prieto et al. 2011). From the previously cited works emerge that is  
193 possible perform polarization analysis using ambient noise, also if pre-processing was applied  
194 to the raw data.

195         Figure 7 b-c shows the particle motion observed for a correlation chosen for its high  
196 signal to noise ratio for a station couple located sufficiently far apart (211 km, station pair  
197 KIF-LP51) to separately analyse the participle motion of the Rayleigh waves and the two

198 early hypothesized body waves. We used the *ZR* and *ZZ* components of the noise correlations  
199 to obtain their particle motion and compare it with the one computed for a vertical force  
200 acting onto the Earth's surface. The particle motions are shown in three time windows, which  
201 correspond to the Rayleigh wave and the two hypothesized body waves.

202         The agreement between particle motion as observed on synthetic seismograms and  
203 noise correlations is striking. The Rayleigh waves have, as expected, an elliptical particle  
204 motion with very similar ratio between the *ZR* and *ZZ* axis. The PmP wave is linearly  
205 polarized, with a coefficient of rectilinearity  $\sim 0.9$  ( $\sim 1$  on the synthetic polarization), and  
206 polarization angle of  $\sim 52^\circ$  as compared to vertical, which is very similar to the  $\sim 56^\circ$   
207 observed on the synthetic motion. The SmS polarization is more complex due to free surface  
208 conversion. A linearly polarized SV wave incident at free surface beyond the critical  
209 conversion angle create phase shifted reflected SV wave and an evanescent P wave (Aki and  
210 Richards, 1980). The result of this sum of differently polarized waves can be observed in the  
211 synthetic seismograms as an inclined, elongated elliptic like polarization. Remarkably, the  
212 polarization on the noise correlations is in very good agreement with the synthetics also for  
213 these waves. This is a strong argument in favour of our interpretation of these waves as SmS.

## 214 **CONCLUSION**

215         The noise correlations from the northernmost part of the Baltic Shield are dominated  
216 by fundamental mode Rayleigh and Love waves. In addition to these waves, we observe  
217 coherent phases up to 500km inter-station distance which have an apparent velocity higher  
218 than the one observed for the fundamental mode surface waves. The fast waves are relatively  
219 high frequency (0.5-2Hz) and non-dispersive in that frequency range.

220         The comparison with earthquake records from a local event also showed the presence  
221 of these waves, and synthetic seismograms were also in excellent agreement with the noise

222 correlation. The synthetic seismograms very clearly points towards identifying the fast waves  
223 as single and multiply Moho reflected P and S waves, an interpretation which is supported by  
224 the wave polarization for different time windows. Note that the agreement between noise  
225 correlations and synthetic seismograms was dependent on the use of a crustal model based on  
226 active seismic studies (e.g. Janik et al., 2007), complemented with low S-wave and Q values  
227 in the uppermost crust as observed locally by Pedersen and Campillo (1991) along a 200km  
228 long profile south of the present study area to obtain similar surface/body wave amplitude  
229 ratios. A first conclusion of this study in terms of the local crustal structure is therefore that  
230 the low S-velocity and low Q model is widespread over the whole study area.

231         The conditions that need to be met for a successful and systematic use of body waves  
232 for lithospheric studies are still uncertain. The first issue is the minimum amount of data  
233 needed to observe the body wave contribution to the Green's function. Theoretically the  
234 correlation function converges to the complete Green's function as the square root of the time  
235 over which the correlation is evaluated. Such duration dependency is also present in our  
236 correlations, when we calculate the amplitude ration of the PmP phases and the remnant  
237 fluctuations for different durations of analysis. For the data at hand, good PmP arrivals with  
238 an acceptable Signal to Noise Ratio (SNR) are observed after just one month of time  
239 averaging. This suggests that travel time measurements can be performed even with limited  
240 reording duration.

241         The second issue is how the noise source distribution and its distance from the array  
242 affect the high frequency noise correlations. A previous study south of our study area  
243 (Pedersen et al., 2007) points towards the generation of the high-frequency seismic noise  
244 along the eastern Atlantic coastline during the winter season. This could potentially have a  
245 major impact on our observed noise correlations, and possibly explain the time asymmetry of  
246 the observed body waves. For such distant sources, two situations can be hypothesized.

247 Firstly, the presence of scattered energy from structures outside the study region can strongly  
248 contribute to the convergence of the correlation to the Green's function by producing an  
249 isotropic, equipartitioned field around the stations. If the stations considered are close  
250 enough, and scattering and attenuation weak enough, ballistic waves can still be observed with  
251 sufficient amplitude to emerge from the fluctuations. In a second situation, if the scattering  
252 and attenuation are strong along the path between the two stations considered, the  
253 identification of weak ballistic arrivals hidden in the correlation fluctuations will be  
254 impossible. These issues are explored in Larose et al. (2008) who presented a heuristic model  
255 for the SNR in correlations of signals considering specifically the role of scattering in  
256 heterogeneous media. Note that the SNR is the ratio between actual Green function and the  
257 remnant fluctuation level of the correlation. The SNR is expected to decrease with increasing  
258 absorption and with distance. In presence of scattering, Larose et al. (2008) also showed that  
259 the SNR is behaving following two regimes: SNR is increasing with scattering strength for  
260 distances smaller than the transport mean free path  $l^*$ , while it is decreasing with scattering  
261 strength for distance larger than  $l^*$ . This is in agreement with the fact that regional body  
262 waves have so far been detected in cratons (Zhan et al., 2010, this study), characterized by  
263 weak attenuation and large mean free path. In Finland, attenuation measurements for S wave  
264 in the crust (Uski et al., 1996) suggest that the mean free path is at least on the order of the  
265 aperture of the LAPNET network. Further work must be carried out to explore whether body  
266 waves can be extracted for all types of crustal structure,.More precisely, in strongly  
267 heterogeneous crustal structures, wave scattering could be sufficient to reduce the amplitude  
268 of the body waves to a point where they would be hidden in the fluctuations of the correlation  
269 functions. The result we report here is encouraging even though more work is required to  
270 demonstrate whether our results can be generalized to other geological contexts to open the  
271 possibility of the use of noise derived body waves for systematic imaging of the Earth's

272 interior.

273

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299

300           **REFERENCES**

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362 Figure 1: Map of the geometry of the POLENET/LAPNET array. The black circles  
363 correspond to the broad-band stations used in this study. The red square in the north-  
364 eastern corner of the array shows the location of the earthquake used to compare the  
365 signals with the correlations.

366

367 Figure 2: Cross correlations of vertical (ZZ) components stacked over 1 year (2008) plotted as  
368 a function of the inter-station distances in the 0.5-1 Hz frequency band. The correlation traces  
369 are organized so that the positive time axis corresponds to energy propagating from the  
370 easternmost to westernmost of the two stations. Rg indicates Rayleigh waves, SmS indicates  
371 the waves that we interpret as S waves reflected from the Moho discontinuity (both first and  
372 second reflection).

373

374 Figure 3: Cross correlations of radial (RR) components stacked over 1 year (2008) plotted as  
375 function of the inter-station distances in the 0.5-1 Hz frequency band. The correlation traces  
376 are organized so that the positive time axis corresponds to energy propagating from the  
377 easternmost to westernmost of the two stations. Rg indicates Rayleigh waves, and PmP  
378 indicates the waves that we interpret as P waves reflected from the Moho discontinuity.

379

380 Figure 4: Cross-correlations of transverse (TT) components stacked over 1 year (2008) plotted  
381 as function of the inter-station distances in the 0.5-1 Hz frequency band. The correlation  
382 traces are organized so that the positive time axis corresponds to energy propagating from the  
383 easternmost to westernmost of the two stations. L indicates Love waves.

384

385 Figure 5: Comparison of the acausal part of (a) ZZ and (c) RR cross correlations plotted as

386 function of inter-station distances and (b) vertical, (d) radial component earthquake data  
387 plotted as function of epicentral distances. All the signals are filtered between 0.5 and 1 Hz.  
388 SmS and SmS2 indicate respectively the first and second S wave Moho reflection, while PmP  
389 indicates the P waves Moho reflection and Rg the Rayleigh waves.

390

391 Figure 6: Comparison of the acausal part of the (a) ZZ, (c) RR cross correlations plotted as  
392 function of inter-station distances. b) shows the vertical component (Z) of synthetic  
393 seismograms using a vertical point force (VF). d) shows the the radial component (R) of  
394 synthetic seismograms using a horizontal point force (HF) at the surface. All the signals are  
395 filtered between 0.5 and 1 Hz. The naming of the waves is the same as in previous figures.

396

397 Figure 7: a) particle motion analysis for the cross-correlation between the station KIF-LP51,  
398 ZZ is the vertical-vertical correlation, ZR is the vertical radial correlation. Red line on the  
399 PmP particle motion analysis shows the result of the linear regression of the ZZ and ZR  
400 motion, the coefficient of linearity is 0.87 and the polarization angle is  $52^\circ$  to vertical. b)  
401 particle motion analysis for synthetic seismograms calculated for the same distance between  
402 the station KIF-LP51, ZVF is the vertical synthetic seismogram generated using a vertical  
403 point source at the Earth surface, RVF is the radial synthetic seismogram generated using a  
404 vertical point source at the Earth surface. The red line on the PmP particle motion analysis is  
405 the linear regression of the ZVF and RVF motion, the coefficient of linearity is 0.99 and the  
406 polarization angle is  $56^\circ$  to vertical.

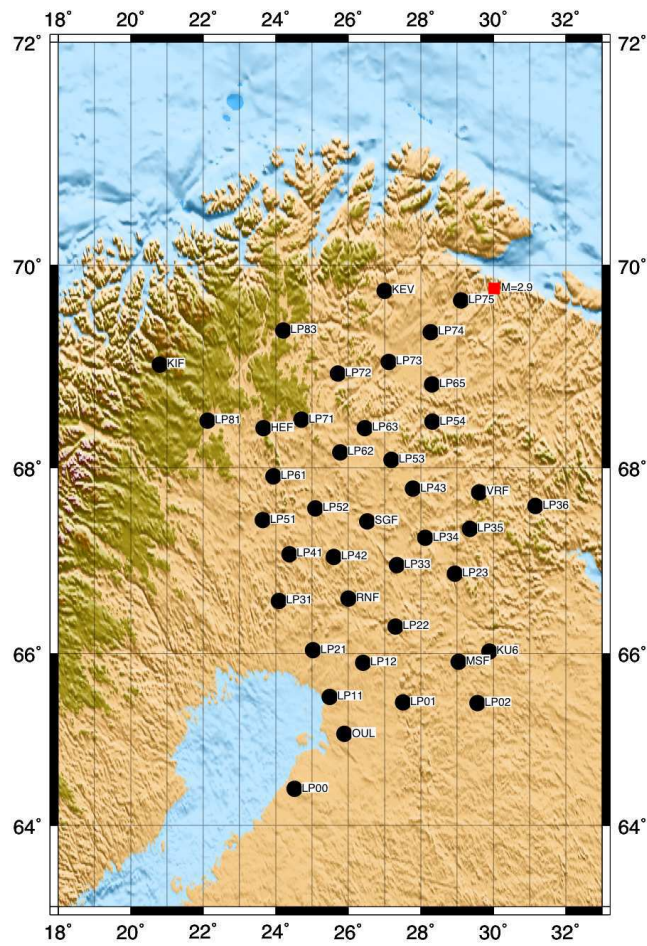
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408 Table 1 : Crustal model used to calculate the synthetics seismograms.  $V_p$  is the P  
409 wave velocity,  $V_s$  is the S waves velocity,  $Q_p$  is the P waves quality factor and  $Q_s$  is the S

410 waves quality factor.

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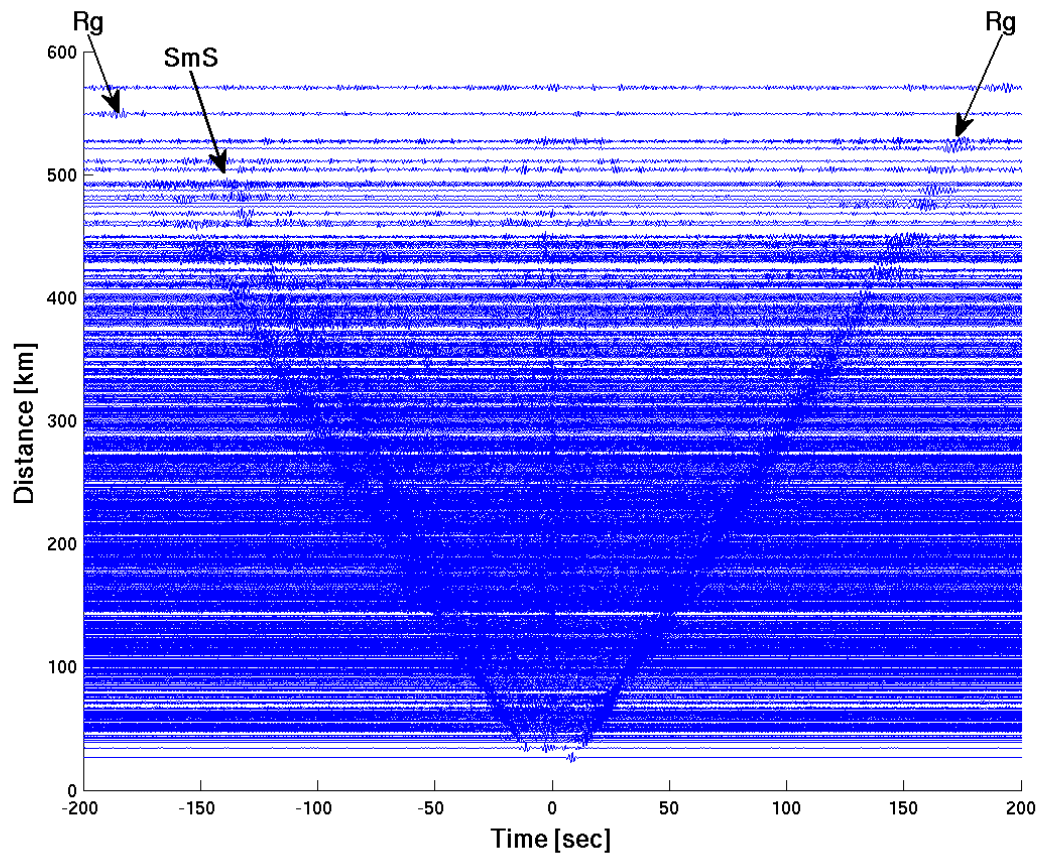
Figure 1

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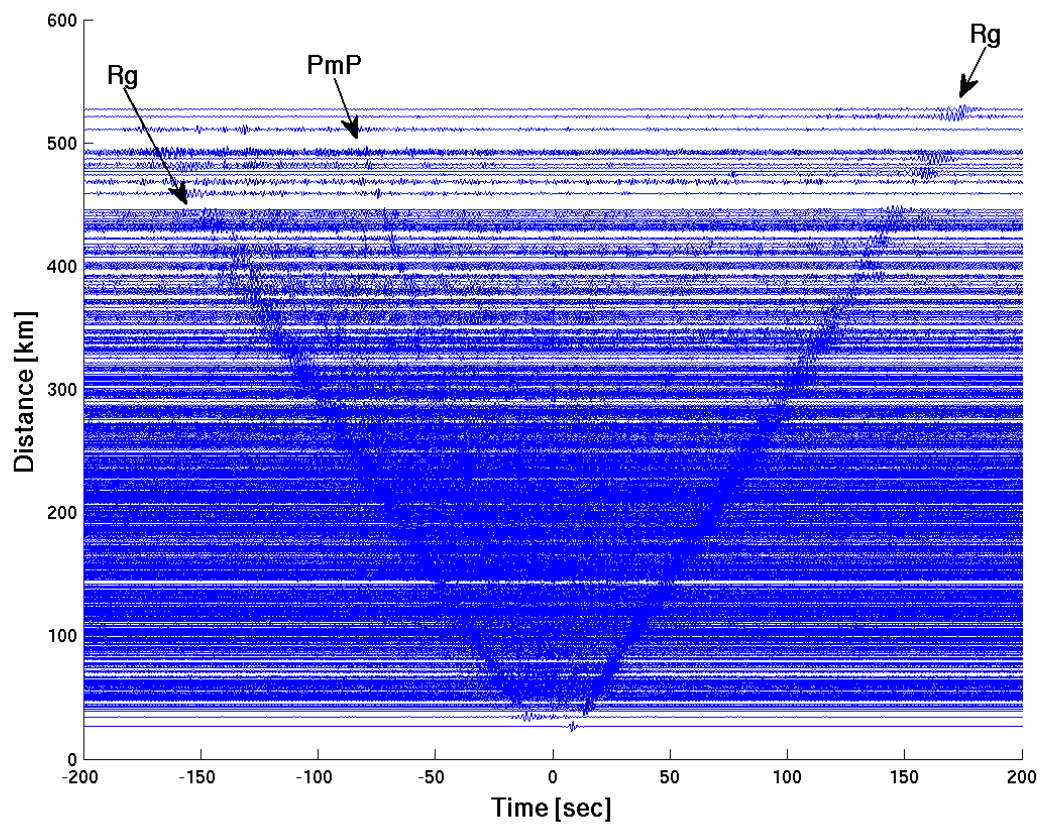


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Figure 2

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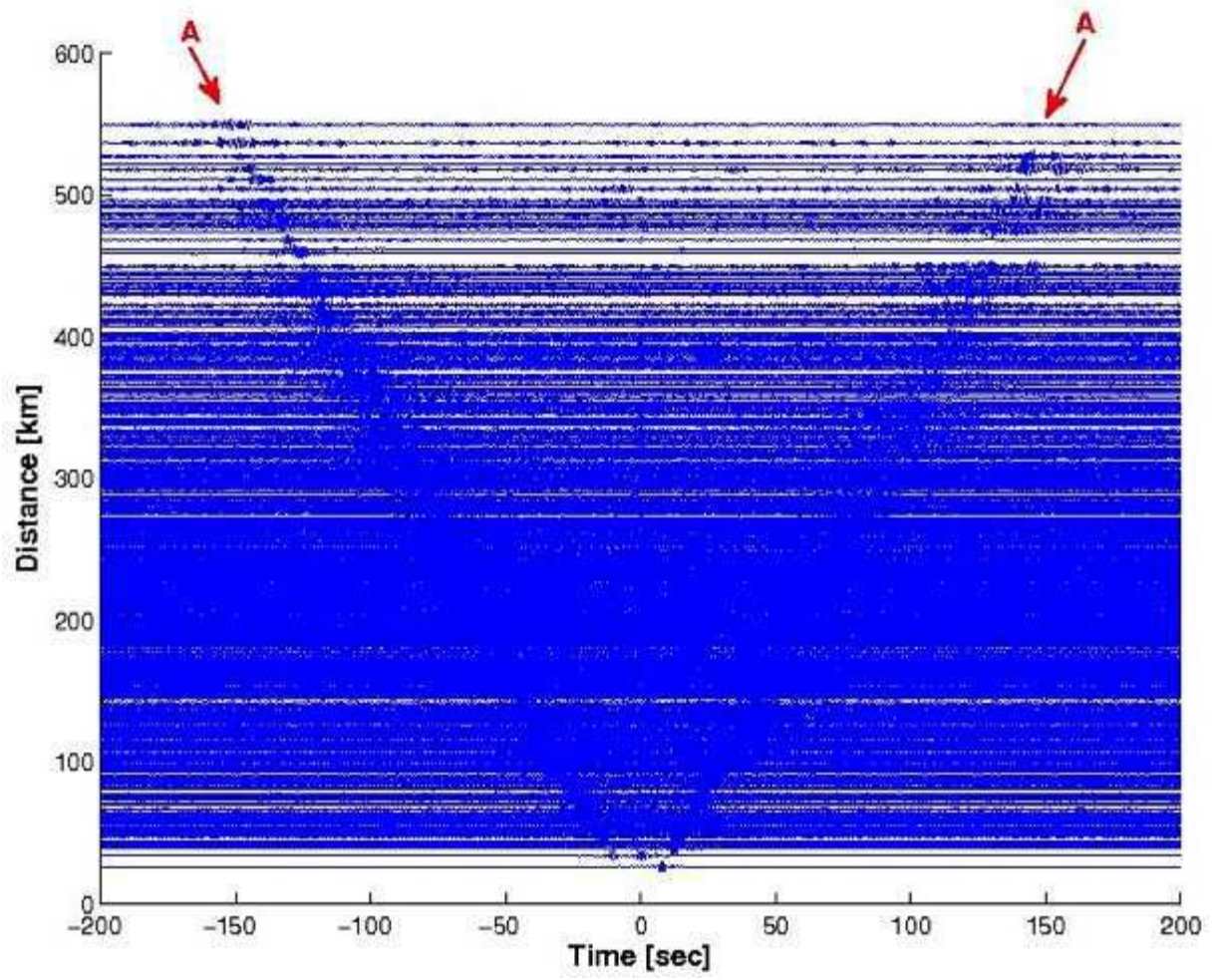


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Figure 3

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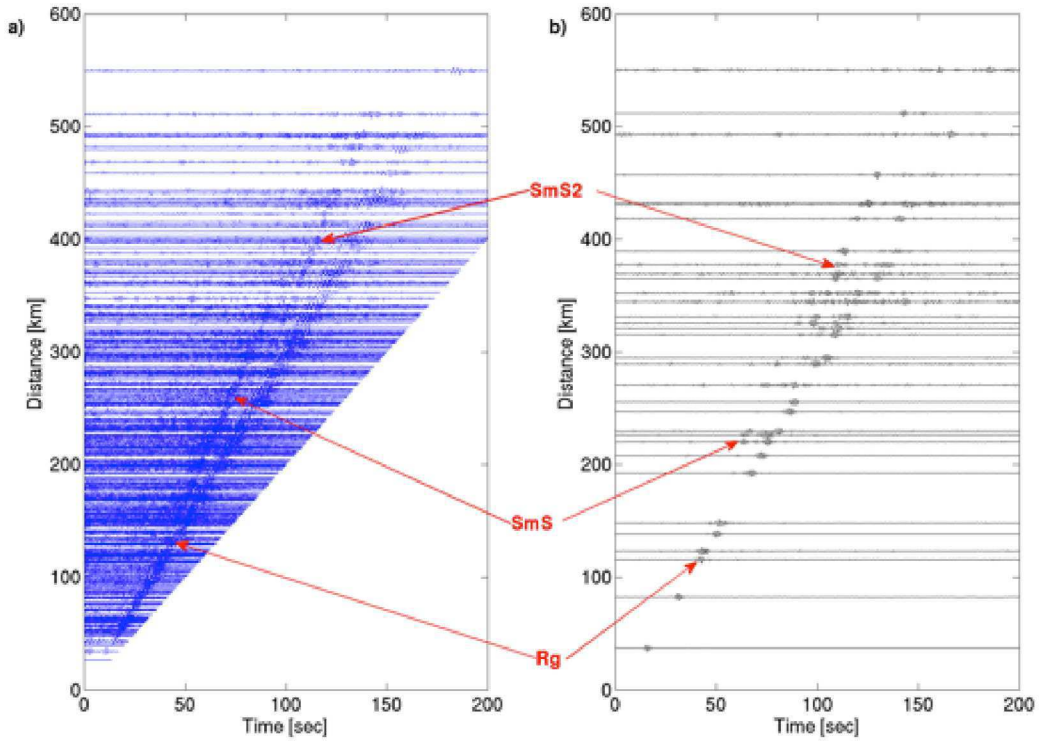
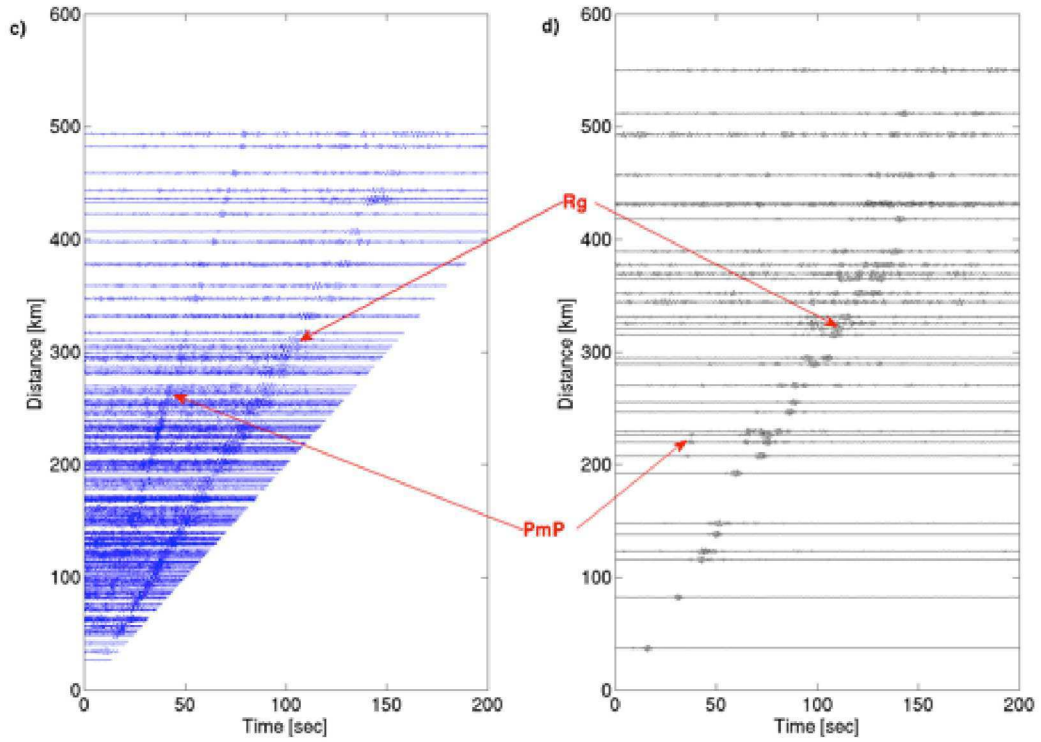


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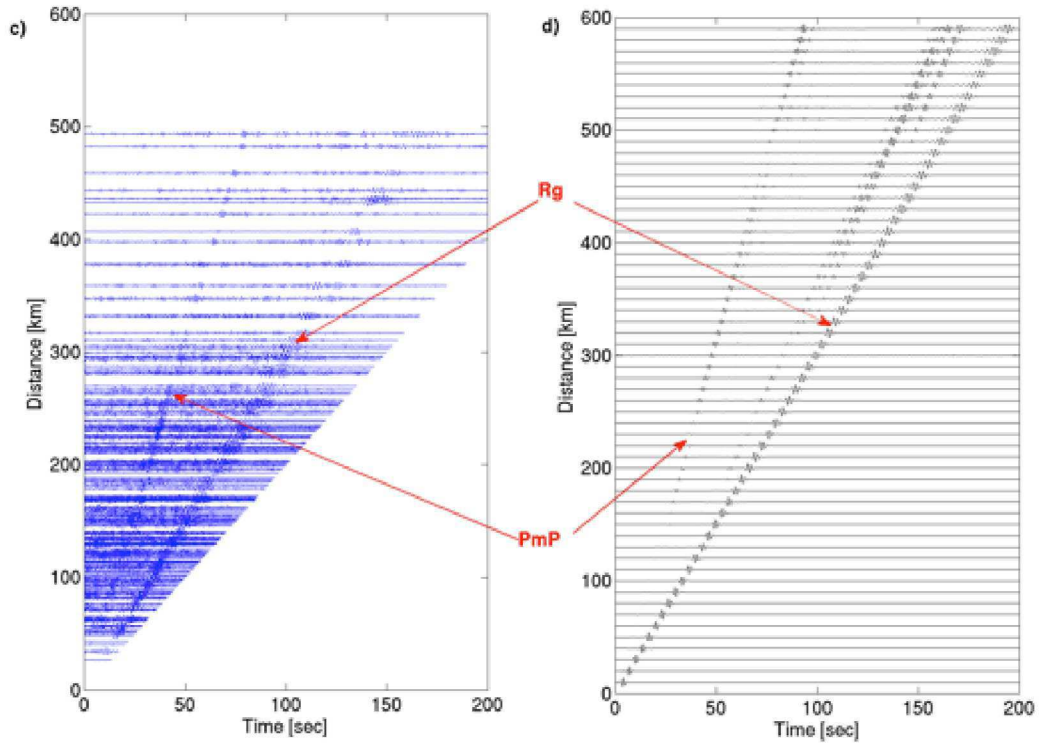
Figure 4



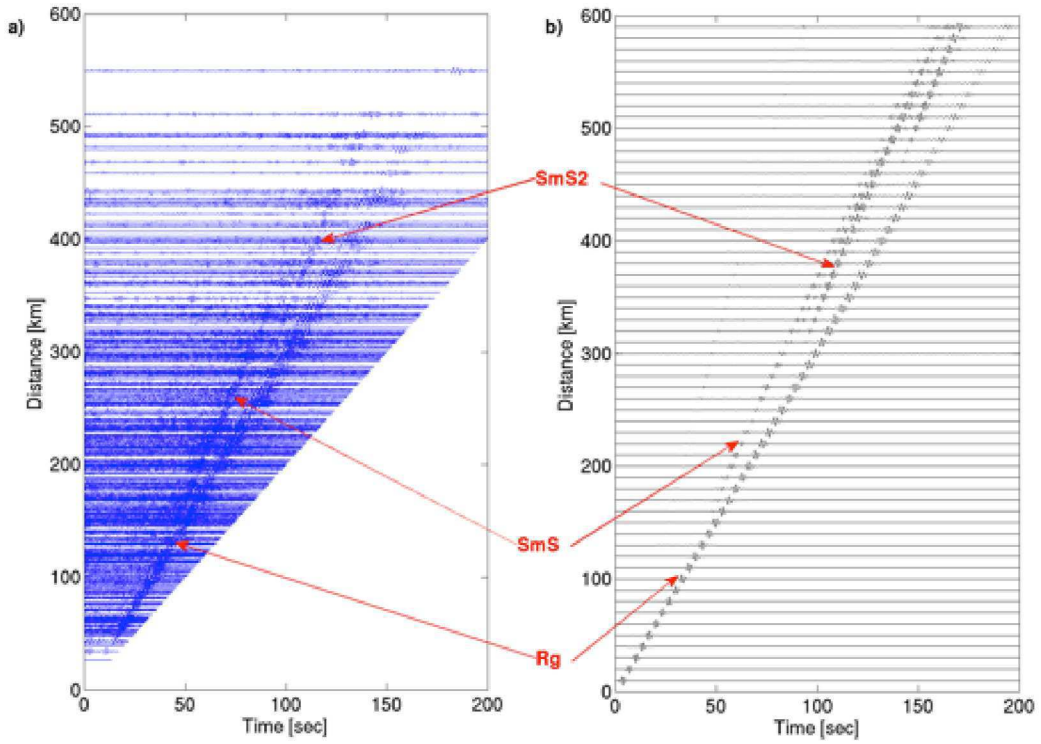




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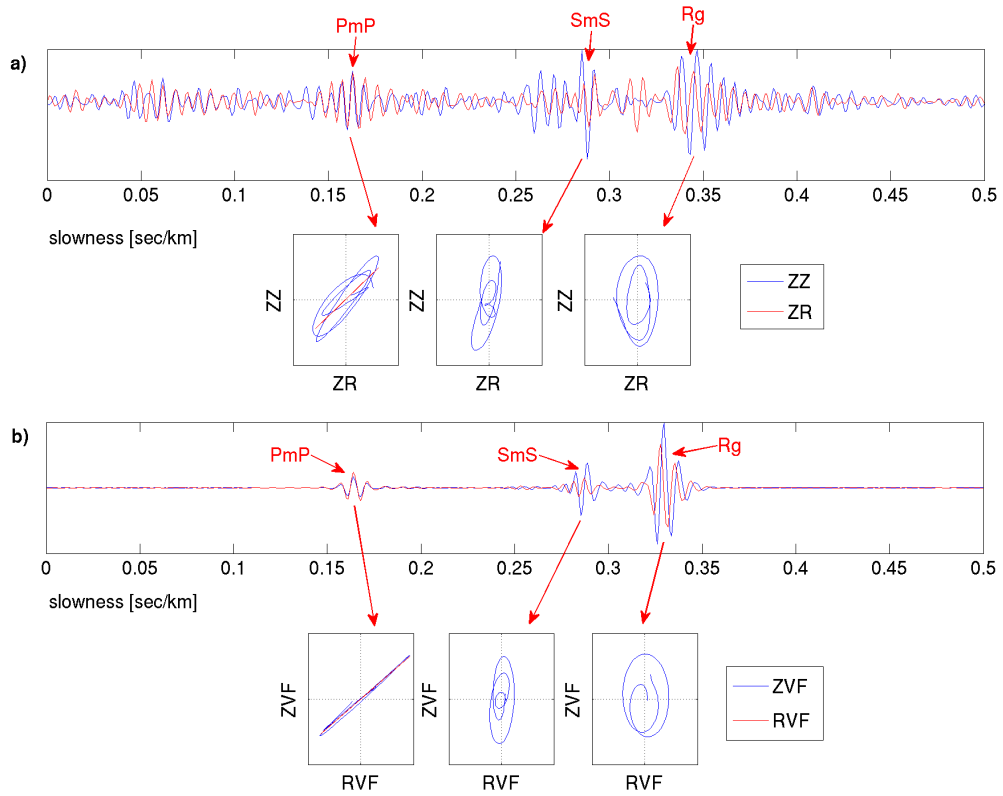
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Figure 6



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Figure 7

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Table 1

<b>Depth (km)</b>	<b>Vp (km/s)</b>	<b>Vs (km/s)</b>	<b>Qp</b>	<b>Qs</b>
<b>0</b>	5.85	3.40	1000	100
<b>3</b>	6.30	3.65	1000	1000
<b>18</b>	6.60	3.85	1000	1000
<b>38</b>	7.15	4.00	1000	1000
<b>40</b>	7.40	4.06	1000	1000
<b>44</b>	8.03	4.62	1000	1000

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