Body wave observations from cross-correlations of ambient seismic noise: A case study from the Karoo, RSA

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Received 6 April 2011; revised 25 May 2011; accepted 31 May 2011; published 12 July 2011.

[1] In the past decade the analysis of seismic noise has become an efficient tool to recover the Green's function between pairs of receivers by cross-correlation of seismic traces. Most studies focus on the investigation of the surface wave component of the ambient noise. Several attempts to recover the body wave part of the Green's function have been documented. In this paper I present the results of cross-correlation of seismic noise and the retrieval of refracted and reflected P-waves along a seismic line in the Karoo region (Republic of South Africa). Body wave refractions (direct phases) and reflections have been observed in the Green's functions derived from ambient noise records of up to 60 hours. The results are compared with shot gathers from a controlled source experiment (borehole explosions), carried out along the same line. The significant potential of ambient noise analysis, especially with respect to P-wave reflections will be shown and discussed. **Citation:** Ryberg, T. (2011), Body wave observations from cross-correlations of ambient seismic noise: A case study from the Karoo, RSA, *Geophys. Res. Lett.*, *38*, L13311, doi:10.1029/2011GL047665.

1. Introduction

[2] The analysis of the ambient seismic noise to recover structural information below the seismic stations has become a wide spread application. In traditional seismic methods the characteristics (origin, time, etc.) of the source have to be known to infer the structure of the Earth. Techniques for deriving the Green's function from ambient noise measurements require spatially well distributed seismic sources. Otherwise, however, it is not required to know anything about the seismic sources. For an overview of the technique, also termed seismic interferometry, see *Wapenaar et al.* [2008], *Schuster* [2009], *Campillo and Paul* [2003], *Shapiro et al.* [2005], and *Bensen et al.* [2007]. By cross-correlation of diffuse wavefields (i.e. noise), the Green's function or seismic impulse response can be recovered, assuming that the noise sources are randomly distributed. Most of the research and application of this technique focusses on the retrieval of surface waves [i.e., *Campillo and Paul*, 2003; *Shapiro et al.*, 2005]. However, theoretical [*Claerbout*, 1968; *Wapenaar*, 2003; *Mikesell et al.*, 2009; *Poletto and Farina*, 2010; *Forghani and Snieder*, 2010] and practical studies [*Scherbaum*, 1987a, 1987b; *Roux et al.*, 2005; *Brown et al.*, 2009; *Draganov et al.*, 2007, 2009; *Landès et al.*, 2010; *Shapiro and Campillo*, 2004; *Wang et al.*, 2010] have shown that not only surface waves, but also body waves (refracted and reflected P-waves) can be extracted from the noise recordings, although *Forghani and Snieder* [2010] have shown that the body wave arrivals can be underestimated under specific conditions when noise sources and receivers are at the Earth's surface. The body wave response, especially the reflections, have the significant potential of directly imaging the subsurface structure. In the present paper I show a data example of P-wave reflections retrieved from noise and compare the derived pseudo (or virtual) shot gathers with controlled source (explosion) seismic gathers, to demonstrate that the observed seismic phases indeed represent P-wave reflections and, thus, can be used for structural imaging purposes. Unfortunately body waves derived from ambient noise have a systematic problem. The potential non-ideal distribution of the sources of the most prominent phase, i.e. surface waves, causes specific artifacts which travel at higher apparent velocities, arriving at earlier times than the predicted arrival time of the surface wave. These artifacts cover a time window where the direct/refracted body wave is also expected. Fortunately, the main frequency content of the surface waves is much lower than that of the body waves and, thus, can be suppressed by simple band-passing.

2. Experiment and Data Processing

[3] In 2005 several seismic experiments have been conducted in the Karoo Basin and adjacent Cape Fold Belt in RSA targeting the crustal reflectivity and velocity structure [*Lindeque et al.*, 2007; *Stankiewicz et al.*, 2007] (see Figure 1). The reflection seismic imaging investigations of *Lindeque et al.* [2007] consisted of a seismic profile of ~100 km length with 182 borehole shots. These shots have been recorded using a roll-along technique with a spread of 180 vertical component, short-period geophones, spaced 100 m apart. Instead of recording the shots only, continuous recording of the wavefield of up to ~60 hours at every location was a "by-product" of the observational technique. For the reflection seismic processing only the appropriate shot time windows have been analysed and an image of the crustal reflectivity of the Karoo Basin has been derived and interpreted [*Lindeque et al.*, 2007]. As a main feature, *Lindeque et al.* [2007] found that the upper crust of the Karoo Basin is dominated by a flat lying band of reflectors associated with Phanerozoic-Mesozoic Cape and Karoo Supergroup sedimentary rocks (for more details see *Lindeque et al.* [2007]). Here, I present the results of a study of the remaining recordings, i.e. pseudo-shot gathers based on the analysis of the ambient noise were derived. The data analysis follows mainly the procedure of *Bensen et al.* [2007]. The originally continuous data (vertical components) were split

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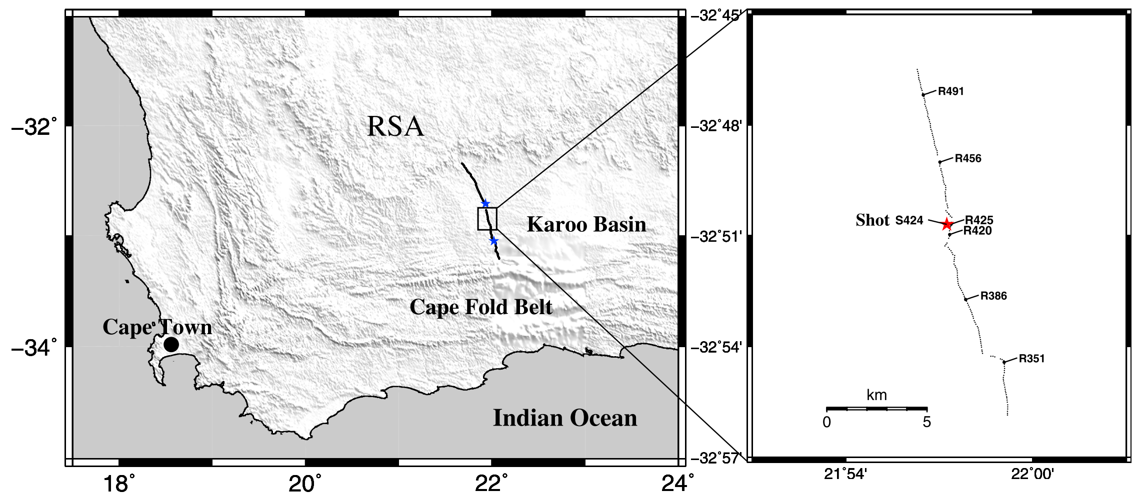

Figure 1. (left) Map of southern Africa showing the study region, (right) zoom on part (18 km length) of the seismic line indicating the location of the borehole shot (star) and the seismic recorders (dots).

into one hour slices, excluding those time windows when borehole shots were fired. The data were one-bit normalized, cross-correlations of station pairs were calculated in the frequency domain and subsequently stacked. The overall length of the analysed noise recordings is from 30 to 60 hours. The correlation function, defined for positive and negative correlation times, represents seismic waves traveling from station 1 to station 2 and vice-versa. When cross correlating one station against all other stations, positive and negative correlation times correspond to pseudo-shot and pseudo-receiver gathers, respectively. Here only pseudo-shot gathers are considered and compared to their borehole shot equivalents.

3. Results

[4] A pseudo-section (virtual-shot) was calculated for the station at position R420 (see Figure 1) by cross-correlating the seismic trace of station R420 with all other available traces for the entire recording period of ~60 hours. Figure 2a shows the band-pass filtered (0.5–20 Hz) result. Several different seismic phases can be identified in the pseudo-section (common pseudo-source section). Phases labeled MS indicate the ocean generated microseisms, here at a period of ~2 s. The unfiltered version of this section (not shown) is entirely dominated by microseisms (MS) with periods typically of ~4 s. This is somewhat surprising because only short-period (4.5 Hz) vertical component seismic sensors have been used. However, it can be explained by the quite strong excitation of the microseisms and the proximity of the Indian Ocean (Figure 1). Since the Indian Ocean in the south is the only source of such noise, the microseisms appear to travel through the seismic line only from one side (labeled MS in Figure 2a). As expected, surface waves of non-oceanic origin with frequencies of several Hz appear to be the strongest signals in the record section (SW in Figure 2a). They are Rayleigh waves and their frequency dispersive character can be seen without any further processing. These waves are the phases used routinely for ambient noise tomography. Since their corresponding noise sources (i.e. wind or cultural noise) are distributed approximately equally in space, the travel time branches, for both positive and negative source-receiver offsets are observed.

[5] In addition to the surface waves, a P-phase with a higher frequency of ~19 Hz (labeled P) can be identified in Figure 2a. This phase has an identical apparent velocity compared to the direct P-wave in Figure 2c and is thus interpreted as the direct body wave arrival. A S-wave equivalent of the direct P-wave is much weaker but still visible (S in Figure 2a). Body wave phases are emphasized in the high-frequency band-passed (10–20 Hz) version of the original pseudo-shot section (Figure 2b). A conventional, explosion based shot-gather (Figure 2c) in the vicinity (~500 m distance, S424 in Figure 1) of our pseudo-shot position (R420 in Figure 1) shows all observed corresponding body and surface wave phases, labeled accordingly. Several other pseudo-shot gathers show direct (refracted) body waves (Figures 2e and 2f). In addition to the refracted P-wave I could also identify, although with a poor signal-to-noise ratio, a segment of a P-wave reflection in Figure 2b (labeled R). Another pseudo-shot gather at position R425 (Figure 1) shifted by a few 100 m to position R420, shows a clearer P-wave reflection (Figure 2d). A further analysis of this phase was performed by applying a normal-moveout (NMO) correction to the data. The NMO correction removes ("flattens") the hyperbolic shape of the traveltime of a seismic reflection caused by a horizontal reflector. Figure 3 shows a zoom at the location of the reflector for the NMO-corrected pseudo-shot gather (Figure 3a) and the explosion shot (Figure 3b). A flat coherent seismic signal can be identified as the dominant P-wave reflection of the explosion shot (Figure 3b). Although the signal-to-noise ratio of the corresponding reflector in the pseudo-shot (Figure 3a) is lower than for the explosion data example, the reflector is still detectable. Due to the zero phase signal character of the ambient noise body wave phases their arrival times appear to be slightly earlier than those of the explosion shot gather. The apparent velocities of body wave phases coincide well for pseudo and explosion shot gathers.

[6] In addition to the presentation of a NMO-corrected shot gather, a NMO-velocity scan was performed, i.e. stacking the sections of Figures 3a and 3b for different NMO correction velocities. All traces of Figures 3a and 3b

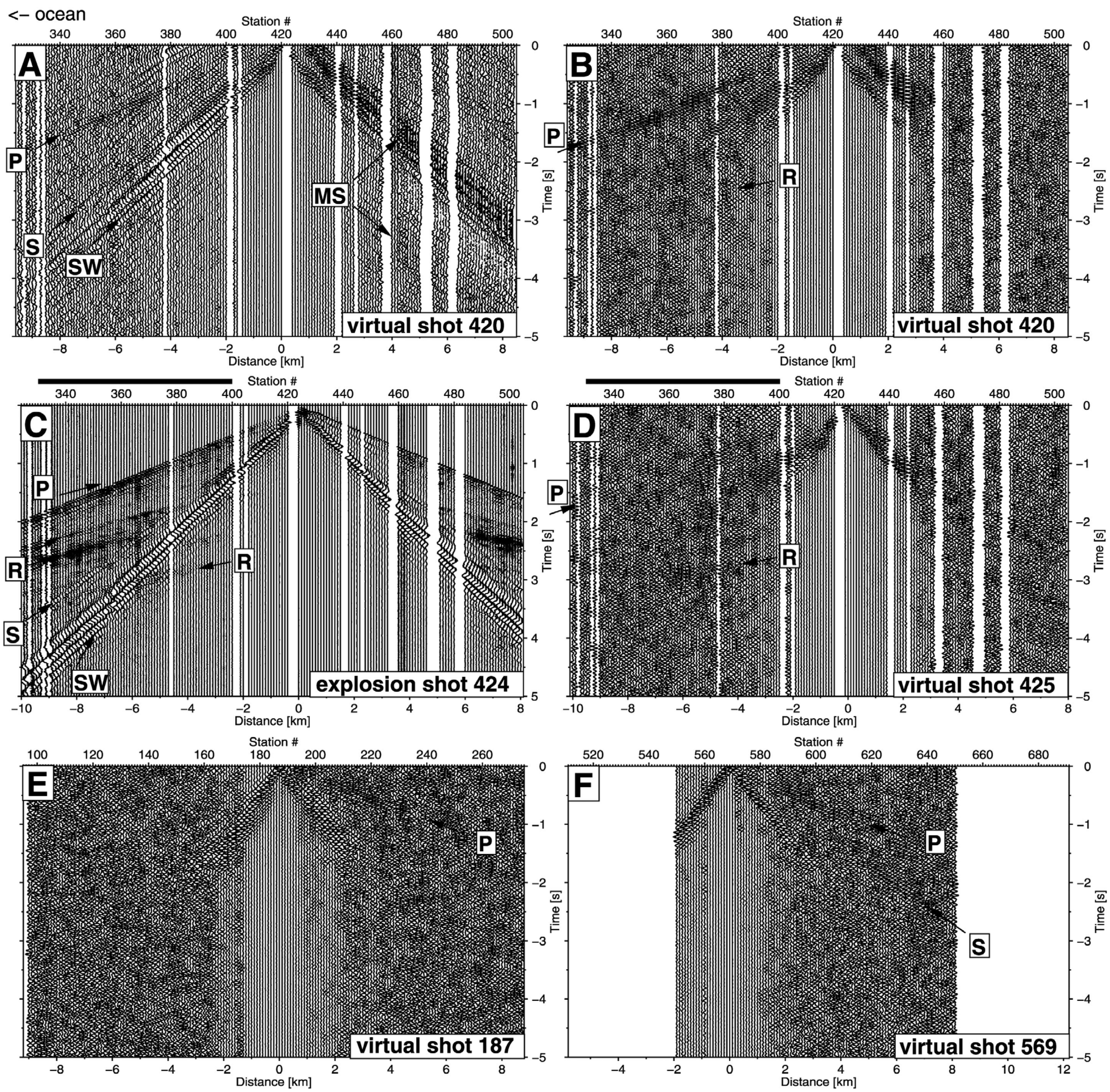

Figure 2. Trace-normalized data examples of shot gathers (locations in Figure 1): (a) pseudo-shot gather for location R420, bandpass filtering (0.5–20 Hz) has been applied. P, S labels indicate the refracted P- and S-phases, SW shows the surface waves and MS indicates the microseisms (black bands of 2 s period), compare with Figure 2c. (b) The bandpass filtered (10–20 Hz) version of Figure 2a. The P-wave reflections are labeled with R. (c) The shot gather from a borehole explosion at the same location as Figure 2a, no filtering was applied. The refracted P- and S-waves, surface waves and P-wave reflection can be easily identified. (d) Another example of a highpass filtered (10–20 Hz) pseudo-record section at a nearby location: R425. Again, the P-wave reflections (R) are visible. (e) Example of a highpass filtered (10–20 Hz) pseudo-record section at location R187, corresponding to the southern blue star in Figure 1. (f) Example of a highpass filtered (10–20 Hz) pseudo-record section at location R569, corresponding to the northern blue star in Figure 1.

(72 traces) were corrected with different NMO-velocities and were stacked to test which NMO-velocity would result in the optimal NMO correction. Figures 3c and 3d show the results of this NMO-velocity scan. Figures 3c and 3d show the specific focussing of the stacking energy at $V_{NMO} \sim$ 3900 m/s for a reflective band between 2.3 and 2.7 s travel time. Due to the lower signal-to-noise ratio of the reflection in the pseudo-shot gather, the focussing effect at ~3900 m/s is less pronounced compared to the borehole shot data. This velocity scan analysis shows that the reflections are not spurious phases, but real reflections with hyperbolic move-outs. Several adjacent pseudo-shot gathers show a similar band of reflections. Unfortunately, the majority of the pseudo-shot gathers calculated for all positions along the

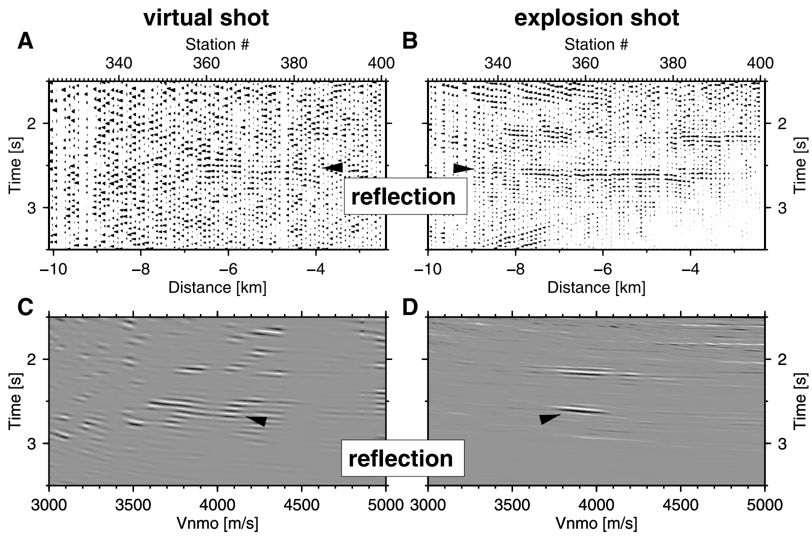

Figure 3. Zoom on data example from Figures 2c and 2d. The bars in Figures 2c and 2d indicate the zoom region. To further improve the visibility of the P-wave reflections, a normal moveout correction (NMO) and bandpass filtering (10–20 Hz) was applied to the data. (a and b) NMO-corrected zooms of the pseudo and real explosion shot gathers. A NMO-correction velocity of 3900 m/s has been applied to the data, transforming the reflection hyperbola to a flat seismic phase, which can now be easily identified. (c and d) NMO-velocity scans, i.e. all traces from Figures 3a and 3b (72 traces altogether), respectively, have been NMO-corrected and stacked. For better identification, the 3rd power of the amplitude is shown. The focussing of the stacked traces at a NMO-velocity around 3900 m/s is a clear indication that the observed seismic phase in the pseudo-shot gather is indeed a P-wave reflection.

seismic line do not show such a clear P-wave reflection and further, conventional reflection seismic processing did not yield a crustal reflection image such as shown by *Draganov et al.* [2009]. To construct such an image it might be necessary to collect longer noise records, since local conditions, i.e. the strength and distribution of noise sources might be different at different study sites. *Forghani and Snieder* [2010] also discussed the conditions of recovery of body waves by ambient noise studies. They found that under specific circumstances related to the imperfection in the noise source distribution, the body wave component of the Green's function is systematically underestimated in the case of noise sources and receivers at the Earth's surface.

4. Discussion

[7] It has been shown in this study that the analysis of up to 60 hours of recordings of seismic noise processed by ambient noise techniques yields pseudo-shot gathers, which have significant body wave arrivals. The high-frequency part of the wave field consists of direct (refracted) and reflected P-waves. These phases have the potential to be used as input for travel time tomography (direct phases) suitable for imaging the shallow velocity structure similar to *Bräuer et al.* [2007] and as input for conventional reflection seismic processing. The latter was unsuccessful with the existing experiment setup shown here, but longer recording times of the ambient noise might solve this problem. Another observation is of interest. While it was possible to recover surface waves for almost all locations along the entire seismic line, the observation of convincingly strong P-wave reflections was only possible for the receiver locations given in Figures 2b and 2d. At these locations the seismic line crosses a busy highway, which might be a pure coincidence. In addition to these locations, direct P-waves (refracted P-phases) have also been observed at several other places along the 100 km long profile, where highway or other man-made generated noise could be definitely excluded as noise sources (for example Figures 2e and 2f, corresponding to locations 24 km south and 15 km north of the highway, respectively). If traffic along a highway is a main source for the excitation of body waves, ambient noise body wave studies could be applied effectively in many areas (i.e. by doing ambient noise reflection seismics along highways). Further studies addressing the issue of ambient noise body wave generation and the necessary duration of noise recordings suitable for body wave recovery are under way. Generally, the exploitation of ambient noise records for "source-less" seismic reflection imaging can have a large potential and might be, assuming sufficiently long ambient noise recordings, a low-cost alternative to controlled source seismic imaging methods.

[8] **Acknowledgments.** I thank all landowners allowing us to deploy seismic stations in the Karoo region, RSA. I thank Michael Weber, Jim Mechie, and the two anonymous reviewers for valuable comments on the paper. Seismic instruments were provided by the GIPP (GFZ Potsdam). All figures were produced with the GMT program [*Wessel and Smith*, 1998].

[9] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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