Monitoring medium changes in an intraplate setting with coda wave interferometry.

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Abstract

This paper presents the application of coda wave interferometry (Snieder *et al.,* 2002) in the case of an intraplate seismic sequence of events located in São Caetano, Pernambuco state, North-East of Brazil in which we report velocity changes related to a 3.7 m_R event in the area.

Firstly, we use synthetic data for a homogeneous and isotropic medium. In our model, the ray path between source and receivers has scatters, which effects are calculated using the technique from Groenenboom and Snieder (1995). The synthetic data shows that minute change in the relative position of the scatters or the source provokes changes in the coda-wave part and that the P-wave early arrival part is not changed.

In the real data set, we first discriminated clusters among our data using P phase cross-correlation. Events with high P-phase correlation coefficient mean that they are collocated. Then from this cluster, we cross-correlated the P phase and the coda wave of every data with a master event separately. We also observe in the real data that whilst the P-wave early part's correlation coefficient remains constant, the coda wave's correlation coefficient exhibit variations. These variations can be interpreted as a result of a change in the medium between the occurrence of the (major) 3.7 m_R seismic event.

Here, we present a case in which this methodology was successfully applied to detect subtle medium subsurface changes in an intraplate setting. We report that even a small 3.7 m_R microseismic event can cause velocity changes in the medium. We also point out that – to the best of our knowledge – examples of velocity changes monitoring for such small magnitude events were not previously reported in the literature.

Introduction

Coda waves correspond to the signal which arrives after the first arrivals. This signal is often considered as noise. However, it has been shown in previous studies that the coda waves are repeatable under the same conditions which prove that they are actually not noise and they carry information about the medium (Grêt, 2004; Snieder et al., 2007; Wapenaar et al., 2010). Several situations can illustrate the different mechanisms of coda-wave creation: i - the case of a wave guide in which the P wave is bouncing back and forth between two boundaries many times; ii - the case of surface waves, in which they can circle the earth many times and iii - heterogeneities in the medium of propagation leading P-wave scattering so that the P wave is going to rebound several time within the medium before being recorded. All these mechanisms lead to the fact that the coda wave is delayed compared to the first arrival wave. In addition, these coda waves, by definition, spend more time in the medium than the first arrival waves. If the medium undergoes a small change, this information will not be perceptible on the first arrivals. However, the coda waves, which spend more time in the medium, "multiply" the intensity of the change making it observable.

Another key element is the concept of interferometry. Interferometry is the comparison between two different signals. It can be two signals from the same source but recorded at two different stations or two signals from different sources, eventually at different date. To compare them quantitatively, we correlate these two signals. The correlation's coefficient (pic of correlation function) is a diagnose of their resemblance while the time shifted is a diagnose of how much the peak is shifted compared to zero lag. The time shifted represents the difference of time arrivals of two similar waveforms. In the case of two different events, it can be the result of two sources that do not occur at the same location (or with different focal mechanism) or a difference in the medium (velocity or heterogeneities) which occurs between the first and the second events.

Several studies already showed the coda waves sensitivity for medium changes and used it for the monitoring of mines, volcanoes, nuclear waste (A. a Grêt, 2004; A. Grêt, Snieder, & Özbay, 2006; Snieder et al., 2007). In this paper, we used coda wave interferometry to detect small changes caused by a small (3.7 m_R) earthquake from an intraplate sequence of events in NE Brazil.

Method

Let us consider two co-located events, recorded by the same station, so they have the same ray path where is the seismic velocity and the propagation time. If we observe a travel-time difference between the two signals we can assume that the medium have changed between the moment when the first event occurred and the moment the second event occurred.

So this travel-time perturbation (δt) is the tool that we use to quantify a change in the medium. We extract δt from the data by the correlation coefficient defined as (R. Snieder, 2002 and A.Grêt, 2004):

$$R^{(t,t_w)}(t_s) \equiv \frac{\int_{t-t_w}^{t+t_w} u_{unp}(t')u_{per}(t'+t_s)dt'}{\left(\int_{t-t_w}^{t+t_w} u_{unp}^2(t')dt' \int_{t-t_w}^{t+t_w} u_{per}^2(t')dt'\right)^{1/2}}$$

where the time window is centered at time t with duration $2t_w$, t_s is the time shifted used in the cross-correlation, u_{unp} is the unperturbed wavefield and u_{per} the perturbed wavefield, δt is the arrival time difference between the waves recorded before the perturbation and the waves recorded after the perturbation.

To analyse the data, we used a matlab toolbox "GISMO suite" (www.giseis.alaska.edu/Seis/EQ/tools/GISMO/) The workflow is: 1) cross-correlation of all the first arrival waveforms between them in order to obtain the cross-correlation matrix and the time lag matrix, 2) determination of groups of similar events into different clusters, 3) cross-correlation of the P phase and coda wave (separately) with a master event from a same cluster.

Synthetics

In order to illustrate our procedure, we produced four set of synthetic data from Groenenboom & Snieder (1995). The first set has been simulated for a source located at the origin (0,0), a scattered medium with 200 scatters and 96 receivers at the opposite side (fig.1).

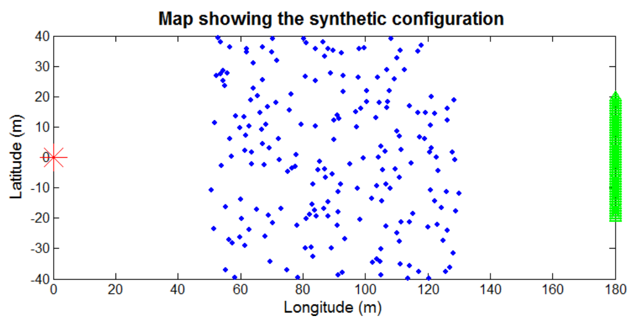

Figure 1: Configuration of the source (red star), the receivers (green triangles) and the scatters (blue dots)

The remaining configuration is as follow: in the second set half of the scatters have been removed, in the third set the strength of the scatters has been changed and in the fourth one, we changed the relative position of the source by moving the receivers four times of 0.8, 1, 1.6 and 2 m respectively in the y-axis. In the second figure, we can observe the effect of these changes on five traces. In the case of a source dislocation of 1.6 meters (fig. 2b), the difference with the initial traces is not so strong, but a waveform difference is visually discernible after the first arrival. On the contrary, a change in the scatters that is either their number (here half the scatters have been removed) or their strength, the difference is more noticeable. In these two last cases, the amplitude of the coda wave decreases strongly. It can be explained by the fact that the coda waves are the result of the scattering, so if we decrease the scattering effect we decrease the coda waves' amplitude.

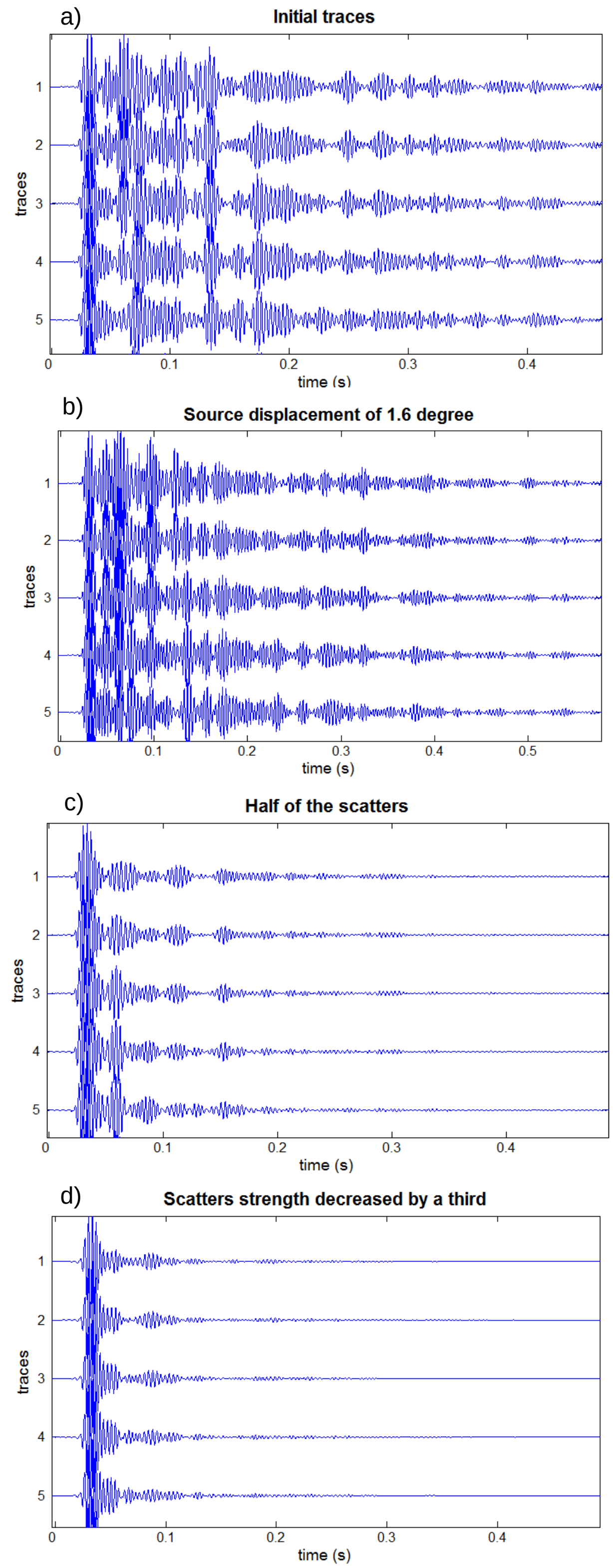

Figure 2: Plot of the five first traces of the synthetics data recorded on the five receivers at the top extremity. The different figures show the initial data (a), the data after a dislocation of the source of 1.6 meters (b), the data simulated with half the scatters (c) and the data when the scatters strength is decreased by a third (d).

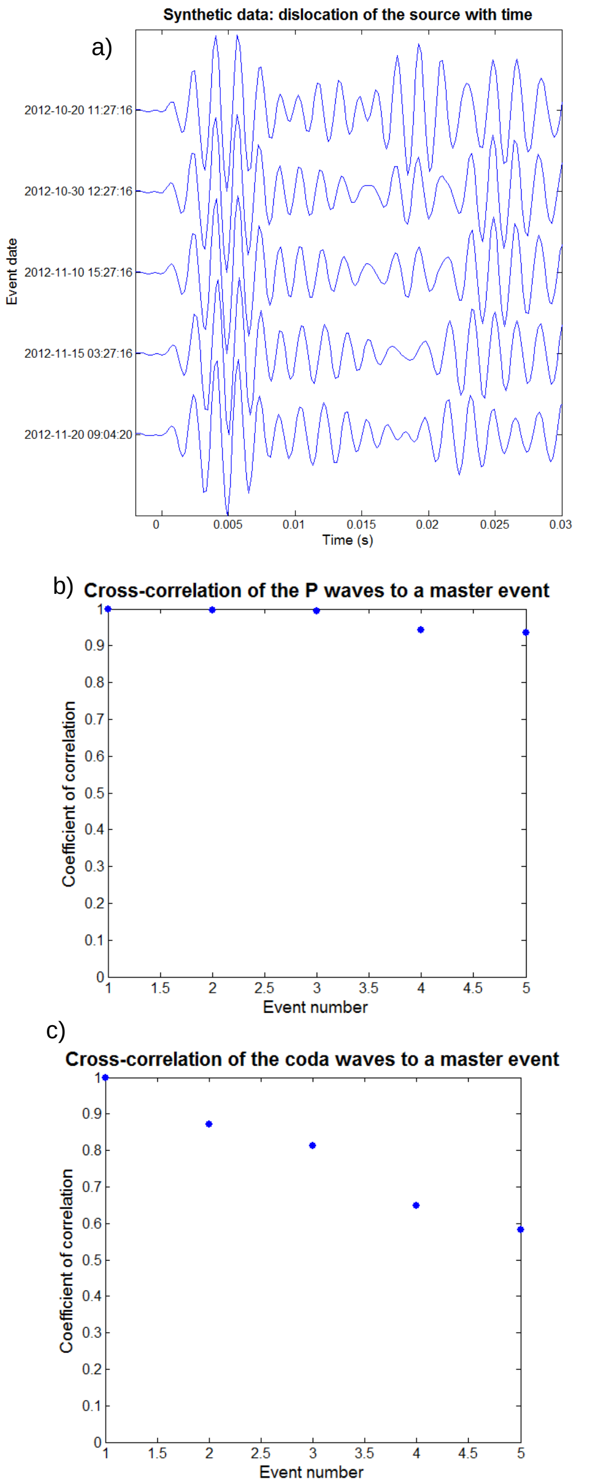

Figure 3: a) Synthetic data recorded by the first receiver. The first trace corresponds to the signal for a source position at the origin and the next traces the source location has been changed for 0.8, 1, 1.6 and 2 meters respectively. b) The figure shows the result of the P wave cross-correlation of all the traces with the first one. c) The figure shows the result of the coda wave cross-correlation of all the traces with the first one.

Figure 3a shows five traces from 0 to 0.03 seconds recorded at the northern receiver. The first trace corresponds to the signal for a source position at the origin and for the next traces, the source location was 0.8, 1, 1.6 and 2 meters respectively. We can observe on this figure (3a) that the signal seems unchanged for the P wave early part (from 0 to 0.005 seconds) along the different traces. Here, these records would indicate that the traces are recording events which are occurring within the same cluster.

Then, we cross-correlated the P phase (from 0 to 0.005 seconds) of all the traces with the first one (occurring on 20/10/2012), and plotted their resulting correlation coefficients in figure 3b. We can observe that these coefficients remain constant with correlation coefficients greater than 0.9, despite the source dislocation. We cross-correlated in the same way the coda waves (from 0.01 to 0.025 seconds) and we can observe that the coda waves' cross-correlation coefficients decrease as the source dislocation increases. It shows that the coda wave is sensitive enough to detect a small change as a source dislocation, whilst the P-wave early parts are not.

Application with real earthquake data

After the study of synthetic data, we studied real data from São Caetano in Pernambuco state in North East of Brazil. These data have been recorded from 01/02/2007 until 21/07/2007. 214 events occurred during this period (Lima Neto et al., 2009) and the event with the greatest magnitude (3.7 m_r) occurred on 20/03/2007. The following events correspond to aftershocks of this main event. The sample rate of these data is 500 Hz. This area is defined by the Pernambuco lineament and its ramifications (fig.4). Short period and broadband seismometers were installed during this period. In this study, we used only the short period stations for practical reasons so in the figure 4 only the stations with short period seismometers are represented (shown as triangles in figure 4). The red triangles correspond to the stations that gave the best results that are represented next.

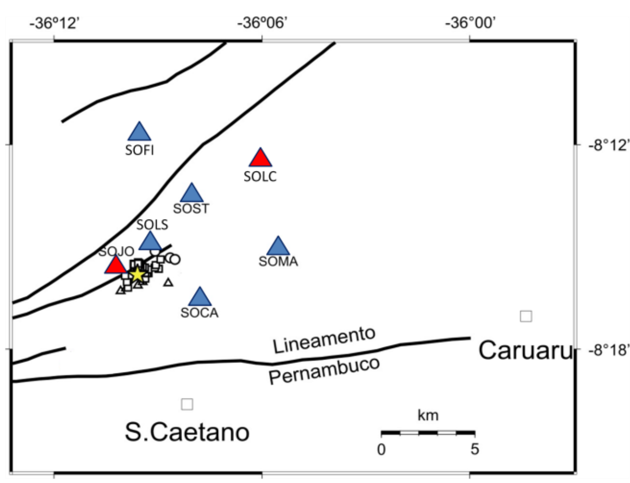

Figure 4: Map showing the fault system, the location of the stations (short period seismometer) and the distribution of the events occurring during the study (small white circles) including the major event (yellow star).

For the study of these data, we followed the same workflow than with the synthetic data. The processing is done station by station. The stations SOJO and SOLC gave the best results. The following figures show the results of the processing for the station SOLC. We first gathered all the signals from this station, cross-correlated the P phase for all the pairs and obtained a cross-correlation matrix (fig.5). From this matrix, we can already determine the main cluster, deliminated by the red square, gathering a group of similar traces.

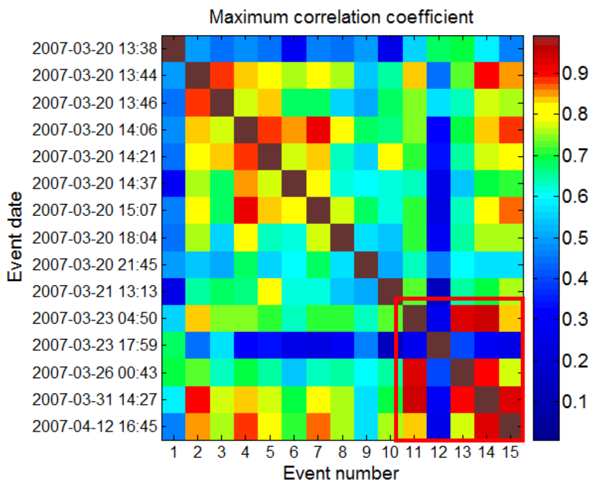

Figure 5: Cross-correlation matrix. The events for which the cross-correlation is marked from 0.8 (yellow) to 1 (red) are considered as well correlated. The red square shows the main cluster (the event on 23/03 at 17:59 is not included in this cluster).

From it, we selected the data that are linked by a P phase correlation coefficient of 0.8 and the group containing the highest number of event is represented by a red square (fig. 6). These similar data are gathered into a cluster (fig. 7). It is composed by four signals from the 20th of March 2007 until the 12th of April 2007.

Then, we filtered the data in two different frequency windows, 32 to 64 Hz and 64 to 128 Hz. The window that we found as being the most representative is 64 to 128 Hz. After, we cross-correlated the coda wave of all the traces with the first one and got their correlation coefficient (fig. 8) from 0.2 to 0.5 seconds. We can observe a variation of the correlation coefficient with time. We see that after the main shock the correlation coefficient rapidly decreases. Then after a few days, this correlation coefficient steadily increases to previous higher values. This sudden drop of correlation coefficient is interpreted by the change of the medium with time due to the main event occurring on 20/03/2007.

As expected, this medium change can be detected by the coda wave and not by the P phase because the coda wave travels more within the medium, making them more sensitive to small changes.

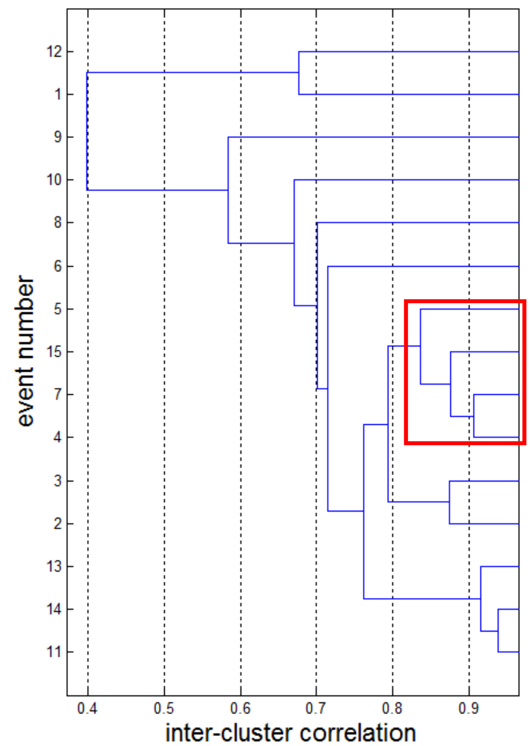

Figure 6: Linkage of the events as a function of their correlation coefficient. The red square shows the main cluster with P wave correlation coefficient superior at 0.8.

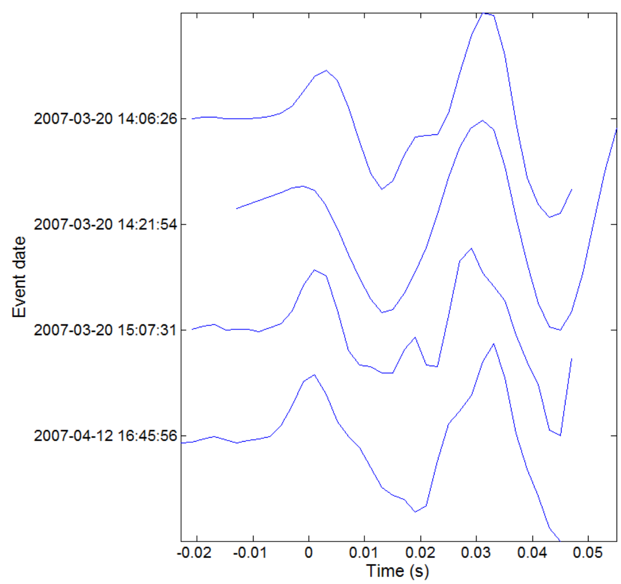

Figure 7: The figure shows the early part of signals from a same cluster determined by the P phase cross-correlation coefficient.

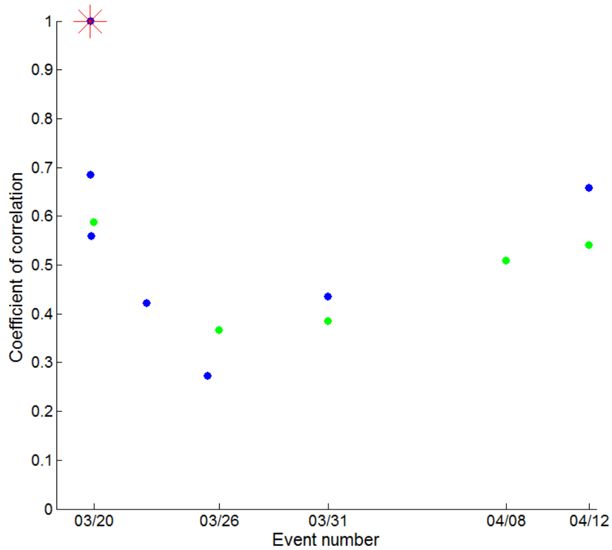

Figure 8: Result of the coda wave's cross-correlation obtains for the main clusters of the stations SOJO (green dots) and SOLC (blue dots) and representation of the strongest event occurring on 20/03/2007 (red star).

In the figure 8, we only represented the result of the main cluster from the stations SOJO and SOLC because these stations gave the best results. From the figure 4, we can observe that this two stations are located on the fault, which could explain that the effect due to the small events is more apparent for these two stations than for the further stations (SOFI, SOCA, SOMA). Concerning the stations SOST and SOLS (located between the SOJO and SOLC stations) following the fault, they did not contain enough events by cluster to give significant results.

Conclusions

In this study, we have presented an approach to detect small changes in a medium related to an intraplate seismic sequence of events in São Caetano, North-East of Brazil, using coda wave interferometry. This study shows, as previous studies, that this technique is very efficient.

We have been able to detect changes with the coda wave interferometry that were not apparent with the P wave. This approach has been checked with synthetic data showing the same behaviour.

Ongoing studies will investigate the nature of the change in the medium that we observed.

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