



**HAL**  
open science

# Assessing Velocity and Impedance Changes Due to CO<sub>2</sub> Saturation Using Interferometry on Repeated Seismic Sources

Louis de Barros, G. O'Brien, C.J. Bean

► **To cite this version:**

Louis de Barros, G. O'Brien, C.J. Bean. Assessing Velocity and Impedance Changes Due to CO<sub>2</sub> Saturation Using Interferometry on Repeated Seismic Sources. 72nd EAGE Conference & Exhibition, Jun 2010, Barcelona, Spain. pp.P402. hal-00523475

**HAL Id: hal-00523475**

**<https://hal.science/hal-00523475>**

Submitted on 5 Oct 2010

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## **Assessing velocity and impedance changes due to CO<sub>2</sub> saturation using interferometry on repeated seismic sources.**

De Barros, G. S. O'Brien, C. Bean

School of Geological Sciences, University College Dublin, Ireland

The injection of CO<sub>2</sub> into saline aquifers produces small changes in seismic properties. The aim of time lapse monitoring is to look for these small variations of the seismic attributes through time, such as the velocity and the impedance, and to relate them to perturbations in the medium properties. However, as injection proceeds, at higher levels of saturation, relative changes in the data become very small. Assuming that a time-lapse seismic survey is a doublet, we can determine the time delay between repeat survey differences, using wave interferometry. These are then related to velocity changes. Additionally, we can do the same for amplitude variations and determine impedance modifications. We investigate the feasibility of this technique on 1) numerical data computed from a simple layered porous medium; and 2) for synthetic data calculated in a more realistic 3D reservoir using a poro-elastic finite-difference solution. In both cases, the reconstructed values are in good agreement with the true modifications.

## Introduction

The role played by the industrial emission of carbon dioxide (CO<sub>2</sub>) in climate change has been well documented. Geological sequestration is a process to store CO<sub>2</sub> in the subsurface in order to reduce emissions of this gas into the atmosphere. Gas and oil reservoirs and saline aquifers are potential subsurface storage sites. For example, CO<sub>2</sub> has been injected into the Sleipner area (Arts et al., 2004; Carcione et al, 2006) for more than 15 years. To prevent risks of leakage, it is necessary to monitor the distribution of the CO<sub>2</sub> when injected and its flow after that. Seismic waves are sensitive to fluid properties through their amplitude and velocity. However, the modifications in the seismic waves can be small as shown by Davis et al. (2003). Particularly, as injection proceeds at higher levels of CO<sub>2</sub>, changes become very small. It is quite difficult to describe the absolute fluid properties, but it is easier to look at relative changes in the medium due to injection and/or fluid movement. We are interested in measuring the differences between data corresponding to two injection times, rather than absolute differences with the baseline data.

Coda wave interferometry has been used in seismology to look at medium changes using seismic multiplets. This method has been used to find wave velocity changes, as shown by Poupinet et al. (1984), and later by Snieder et al. (2002) and Pandolfi et al. (2006). Time-lapse active seismic data can be considered as seismic multiplets and therefore can be used to look for small changes in the medium properties. The density, through the impedance, is a parameter that is more sensitive to the fluid than the velocity. Moreover, in a reflection survey, the wave amplitude can be related to the impedance contrasts. We derive a simple relation between the amplitude change and the impedance contrast. Then, we describe the methodology used to measure both the amplitude and time change in layered media to infer changes in fluid properties following the injection of CO<sub>2</sub>. Finally, we numerically investigate the accuracy of the results in a complex 3D medium.

## Wave interferometry

Interferometry is based on the measurement of time delays, which is then converted into velocity changes  $\delta V$  through the simple relation (Snieder et al., 2002)

$$\delta V/V = -\delta t/t, \quad (1)$$

where  $V$  is the velocity of the medium, and  $\delta t$  is the measured travel time delay. This relation has been defined for an overall change of the medium assuming scattering waves. However, this assumption of a diffusive regime is not valid for simple layered models. We consider a model with a layer  $L_1$  with length  $H$  embedded in a infinite homogeneous medium ( $L_0$ ). Assuming a perturbation  $\delta V_1$  in the layer  $L_1$ , the delay for the reflected waves on the bottom of  $L_1$  is:

$$\delta t = -2H_1/V_1 (\delta V_1/V_1). \quad (2)$$

Equation (2) is equivalent to equation (1) assuming that  $t=2H_1/V_1$ . That means that  $t$  in eq. 1 is the time from the last reflected waves without time delays, i.e. the reflected waves on top of  $L_1$ .

In the same way, we want to relate a small change in the amplitude  $A$  of the reflected waves to a impedance modification. At normal incidence,  $A=(Z_1-Z_0)/(Z_1+Z_0)$ , where  $Z_1$  and  $Z_0$  denote the impedance in layer  $L_1$  and  $L_0$ . A small change  $\delta Z_1$  and/or  $\delta Z_0$  in the impedances will result in an amplitude  $A'=(Z_1+\delta Z_1-Z_0-\delta Z_0)/(Z_1+\delta Z_1+Z_0+\delta Z_0)$ . Assuming that  $\delta Z_1+\delta Z_0 \ll Z_1+Z_0$ , we have

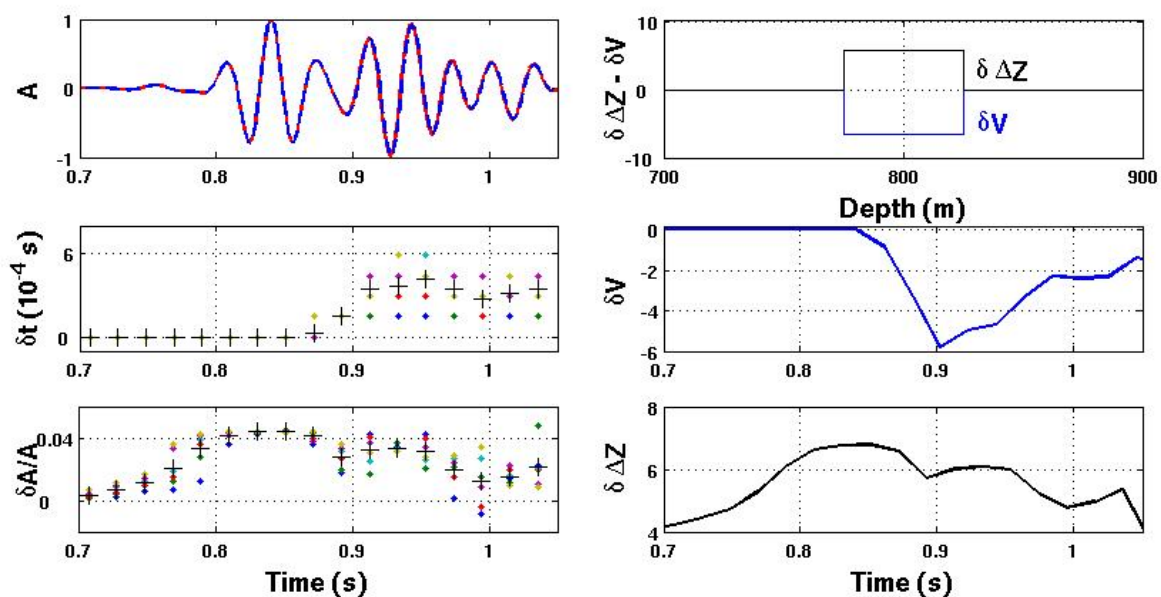
$$\delta A/A = (A'-A)/A = (\delta Z_1 - \delta Z_0)/(Z_1 - Z_0) = \delta \Delta Z / \Delta Z. \quad (3)$$

This relation means that a small relative change in amplitude is equivalent to a relative change in impedance contrast. It can be generalised for the reflected waves from the bottom of the layer, assuming that the impedance contrast is small. Equation (3) is valid under the assumptions of 1) a normal incidence of the reflected waves, 2) a small change in the impedance contrast and 3) a small impedance contrast. However, both relations (1) and (3) are derived only for a change in a simple one-layer model. It is thus necessary to check the behaviour of these relations in the case of more complex geometry.

### Plane layered model

To check the accuracy of the method, we applied it to a simple layered model. We consider a layered porous reservoir between 775 m and 1125 m depth with shale and sand layers. The reservoir is embedded in an infinite medium. CO<sub>2</sub> is injected into the first layer (775-825 m), and we want to quantify a change of a CO<sub>2</sub> saturation from 20% to 40%. Properties of CO<sub>2</sub> are computed using the relations of Batzle and Wang (1992), Carcione et al. (2006). Data are computed at normal incidence for an explosive source (Ricker wavelet, 30 Hz frequency peak) using a reflectivity method (Kennett, 1981) followed by a wavenumber integration method (Bouchon, 1981) in a poroelastic medium (see Pride, 2005 and De Barros and Dietrich, 2008).

True velocity and impedance changes are given in figure 1. We measure the time delay and the amplitude changes using a time windowed cross correlation of the two traces. For each window and measured point, we find the time lag corresponding to the maximum of the correlation coefficient. To be more precise, we use a spline interpolation around it to allow a precision on the delays smaller than the data time step. We then align the two signals and compute the amplitude ratio. The amplitude  $A$  is defined as the square root of the sum of the squared amplitude of the samples contained in the window. To avoid instabilities due to null signals when computing the amplitude ratio, we apply a water level method ( $10^{-6}$  on  $A$  in eq. 3). For every measurement point, we repeat the measures assuming different window lengths (here, 8 measures from half period to 5 dominant periods). If the correlation coefficient is lower than a threshold (here 0.9), values are not kept.  $t$  is computed from the time of the reflected waves at the top of the reservoir. Velocity and amplitude variation are then obtained from eq. (1) and (3).



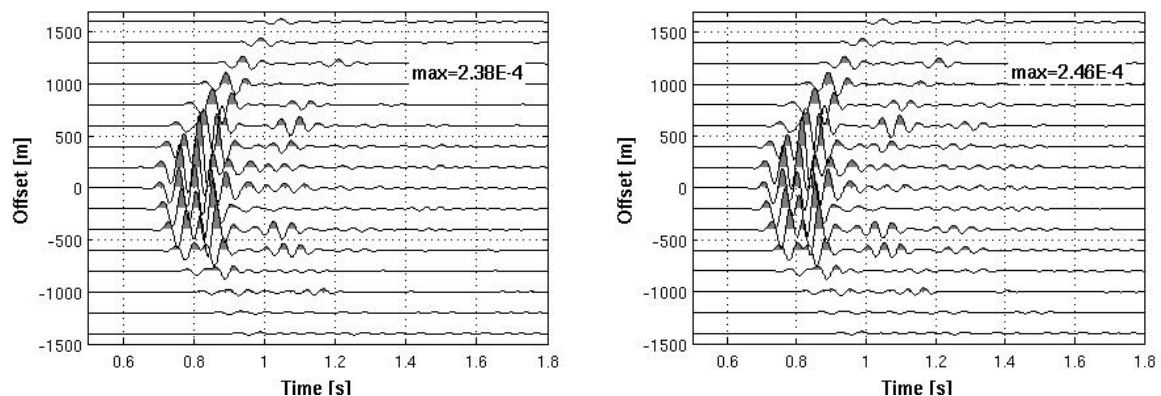
**Figure 1** Application of the method to a layered model. Left) Top: Data computed with 20% (red) and 40% (blue) CO<sub>2</sub> saturation; Middle: measured time delay  $\delta t$ ; Bottom: measured amplitude contrast  $\delta A/A$ . Coloured dots correspond to different sliding window lengths, + signs are the mean values. Right) Top: True model showing velocity and impedance changes; Middle: Estimated velocity

change; Bottom: Estimated impedance change. Note that the true values are given according to depth, while the measured changes are given according to time. The impedance change has been divided by  $10^4$  for figure clarity.

In figure 1, we see that the maximum value obtained for the change ( $\delta V = -5.8$  m/s and  $\delta \Delta Z = 67000$  kg/m<sup>2</sup>/s) are very similar to the true values ( $\delta V = -6.5$  m/s and  $\delta \Delta Z = 61000$  kg/m<sup>2</sup>/s). For this simple case, this method seems accurate. As expected, the velocity change is seen in the reflected waves from the bottom of the perturbed layer, while the change in amplitude is seen by the two reflections, but is more accurate for the reflected waves at the top of the perturbed layer. Finally, the reconstructed changes are smooth, as the entire Ricker wavelet carries information about the perturbation. We computed  $\delta V$  and  $\delta \Delta Z$  in this case as we know  $V$  and  $\Delta Z$ , perfectly. However, in a real case, we can directly estimate a variation of the fluid properties from  $\delta V/V$  and  $\delta \Delta Z/\Delta Z$  using the Gassmann fluid substitution relations.

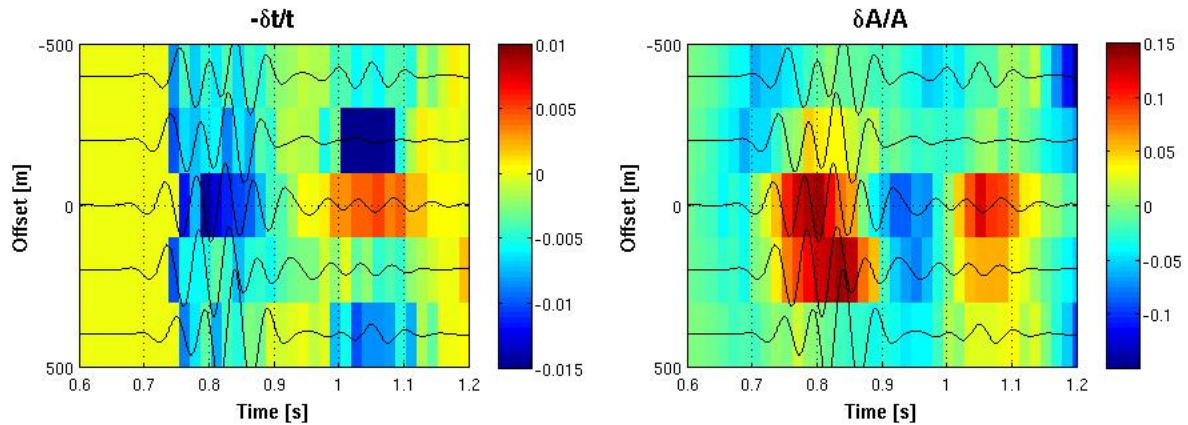
### 3D synthetic reservoir

We use a more complex 3D model with a 80 m thick reservoir, with 5 different facies where the geometry is based on a statistical ensemble of shallow petroleum reservoirs (Manzocchi et al., 2008). Waveforms are computed in a poroelastic heterogeneous medium using the staggered finite difference solver (4<sup>th</sup> order in space, 2<sup>nd</sup> order in time) of O'Brien (submitted). Synthetic data are computed for 1) a medium fully saturated by water (baseline data), 2) a CO<sub>2</sub> saturation of 20% and 3) a 40% saturation in an area with a maximum radius of 200 m where the radius is related to the permeability of the facies. Figure 2 shows the data differences between the baseline and the data with 20% and 40% CO<sub>2</sub> saturation.



**Figure 2** Differential seismograms between reference data and data computed for 20% (left) and 40% (right) of CO<sub>2</sub>. Centre of CO<sub>2</sub> patch and seismic source are located at the zero offset position.

We apply the interferometry method in order to measure the difference between the data corresponding to 20% and 40% CO<sub>2</sub> saturation. To get rid of the energetic waves that do not carry information about the fluid substitution we use the differential data of figure 2. We use the traces closest to the sources, i.e. with an angle of incidence smaller than 15°.



**Figure 3** Left) Time variation  $-\delta t/t$  ( $=\delta V/V$ ) and Right) amplitude variation  $\delta A/A$  ( $=\delta\Delta Z/\Delta Z$ ) measured when comparing differential seismograms of figure 2.

The theoretical mean values for the change are  $\delta V/V=-0.8\%$  and  $\delta\Delta Z/\Delta Z=17.8\%$ . Figure 3 shows the results. We see that both the time delay and amplitude change gave values in good agreement with the true theoretical mean changes. The order of magnitude of these values confirm that the sensitivity to a fluid change is higher for the impedance than for the velocity. A time change is present in all the seismograms and does not allow us to localise the CO<sub>2</sub> change. On the other hand, the amplitude change seems to be located above the medium perturbations.

## Conclusions

Injection of CO<sub>2</sub> (or any other fluid injection or extraction) changes both the velocity and the amplitude of reflected waves. However, the change can be very small and as such, high resolution seismic techniques have to be employed to quantify these changes. One such technique is seismic wave interferometry. It is easy to apply and allows the measurement of very small variations in the velocity and amplitude of the seismic wavefield. We use this method on synthetic active seismic time-lapse data to measure both the velocity and the impedance changes. The time-lapse difference seismograms are treated as seismic multiplets. The preliminary tests on a plane layered and complex 3D models show good agreement between the measured and true values. However, it gives a smooth picture of the perturbations. The relationships between the amplitude contrast and impedance have still to be investigated in more detail, both with analytical and numerical approaches. A direct interpretation of the variations of the seismic attributes into fluid perturbations will also be performed.

## Acknowledgements

Louis De Barros and Gareth S. O'Brien are funded by the department of Communications, Energy and Natural Resources (Ireland) under the National Geosciences programme 2007-2013. We are grateful to ICHEC for numerical computation facilities.

## References

- Arts, R., O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, and B. Zinszner, 2004. Monitoring of CO<sub>2</sub> injected at Sleipner using time-lapse seismic data. *Energy* 29, 1383-1392.
- Batzle, M. and Z. Wang, 1992. Seismic properties of pore fluids. *Geophysics*, 57(11), 1396-1408.
- Bouchon, M., 1981. A simple method to calculate Green's functions for elastic layered media. *Bull. Seism. Soc. Am.*, 71(4):959-971.
- Carcione, J.M., S. Picotti, D. Gei, and G. Rossi, 2006. Physics and seismic modeling for monitoring CO<sub>2</sub> storage. *Pure appl. geophys.*, 163:175-207.
- Davis, T. L., M. J. Terrell, R. D. Benson, R. Cardona, R. R. Kendall and R. Winarsky, 2003. Multicomponent seismic characterization and monitoring of CO<sub>2</sub> flood at Weyburn Field, Saskatchewan. *The Leading Edge* 22, 696-697.
- De Barros, L. and M. Dietrich, 2008. Perturbations of the seismic reflectivity of a fluid-saturated depth-dependent poroelastic medium. *J. Acoust. Soc. Am.*, 123(3),1409-1420.
- Kennett, B.L.N. , 1983. *Seismic Wave Propagation in Stratified Media*. 342 p. Cambridge University Press, Cambridge.

- Manzocchi T., Carter J. N., Skorstad A., Fjellvoll B., Stephen K. D., Howell J., Matthews J. D., Walsh J. J., Nepveu M., Bos C., Cole J., Egberts P., Flint S., Hern C., Holden L., Hovland H., Jackson H., Kolbjørnsen O., MacDonald A., Nell P.A.R., Onyeagoro K., Strand J., Syversveen A. R., Tchistiakov A., Yang C., Yielding G. and Zimmerman R., 2008. Sensitivity of the impact of geological uncertainty on production from faulted and unfaulted shallow marine oil reservoirs - objectives and methods. *Petroleum Geoscience*, 14 :3-15.
- O'Brien, G. S., 3D rotated and standard staggered finite-difference solutions to Biot's poroelastic wave equations: Stability condition and dispersion analysis, submitted.
- Poupinet, G., W. L. Ellsworth, and J. Frechet (1984). Monitoring velocity variation in the Crust using earthquake doublets: an application to the Calaveras Fault, California, *J. Geophys. Res.* 89, 5719-5731.
- Pandolfi D., C.J. Bean and Saccorotti G., 2006. Coda wave interferometric detection of seismic velocity changes associated with the 1999 M = 3.6 event at Mt. Vesuvius, *Geophy. Res. Lett.*, 33, L06306.
- Pride, S.R., 2005. Relationships between seismic and hydrological properties, chapter 8, pages 253-284, *Hydrogeophysics*. Water Science and Technology Library, Springer.
- Snieder, R., A. Gret, H. Douma, and J. Scales, 2002. Coda Wave Interferometry for Estimating Nonlinear Behavior in Seismic Velocity. *Science*, 295(5563), 2253-2255.