AVO Analysis of 3-D/3-C Datasets from Weyburn CO_2 Storage and Monitoring Project

Le Gao* and Igor Morozov
University of Saskatchewan, Saskatoon, SK
le.gao@usask.ca

Summary

Amplitude variation with Offset (AVO) may be a sensitive discriminator for the presence of CO_2 during enhanced oil recovery. The AVO effects also show characteristic variations with changing pressure and CO_2 saturation. Based on the rock physics theory, we studied the AVO attributes for surface seismic data in different vintages, 1999, 2001 and 2002 at the Weyburn and Midale fields in southeast Saskatchewan. By comparing the AVO intercept and gradient variations, pressure-saturation effects can be identified presence of CO_2 may be recognized in an area between two injection wells.

Introduction

The Weyburn-Midale field in southeast Saskatchewan has been undergoing CO_2 injection since October 2000. In order to monitor the injection, CO_2 storage, and oil recovery, 3-D and 3-D/3-C seismic data were acquired nearly annually, starting from a baseline survey in December 1999 (White et al., 2004). The main objective of this monitoring, conducted as a part of the Weyburn-Midale CO_2 Monitoring and Storage Project, is to track and quantify the distribution of CO_2 in the subsurface (White, 2009).

Among the various seismic techniques for CO_2 detection and monitoring in the subsurface, Amplitude variation with Offset (AVO) methods appear to be quite promising. The AVO is measured in the primary P-wave reflections, which are the strongest and freest from contamination, and at the same time, they contain the information about the S-wave reflectivity. Many theoretical models were established based on AVO equations in fluid-, gas- and also CO_2-saturated media; however, still little research has been done on time-lapse AVO attributes in real data. In this paper, the AVO intercept, gradient and S-wave reflectivity are examined on caprock based on seismic data at three earliest vintages of the Weyburn-Midale dataset. Compared with the baseline survey (1999), the two monitor surveys (2001 and 2002) show some differences of their AVO attributes.

AVO results from Weyburn 3-D 3-C dataset

AVO techniques exploit changes in seismic wave amplitudes with incident angles. In an isotropic and homogeneous medium, the exact equations for reflection amplitudes describing the amplitude variations with angles were given by Zoeppritz (1919). Aki and Richards (2002) derived the small-contrast approximation to these equations which is commonly used today. For compressional (P) waves, the reflection coefficient R_{PP}, is related to the incidence angle as follows:

$$R_{PP}(\theta) \approx A + B\sin^2\theta \quad (1)$$

where the intercept, A, is the P-wave reflection coefficient at normal incidence, and the gradient, B, describes the amplitude variation for small angles. The main purpose of the AVO analysis is to detect temporal changes in parameters of A and B.

In order to carry out the analysis of the several vintages consistently and to maintain repeatability of data processing, careful calibration of the pre-stack dataset is required. In this study, we addressed this problem by constructing a multi-vintage, pre-stack dataset that combined the baseline and both monitoring 3-C datasets. (Morozov and Gao, 2009; Ma et al., 2009). The resulting “3×3-C” dataset was then fully calibrated by performing the time shifts, amplitude corrections and spectral balancing in the pre-stack domain. From this calibrated dataset, subsets were again extracted and time-lapse AVO attributes were analysed by using Hampson-Russell software.

Figure 1 shows the AVO intercepts at the caprock above the injection zone for the three years of acquisition. The yellow ellipses between the horizontal injection wells indicate an area of increased AVO intercepts compared to the 1999 dataset. In this area, P-wave amplitudes were increased, which could be caused by CO_2 injection.

Figure 2 shows the corresponding AVO gradients at different vintages. In these images, the AVO gradients also appear to increase with injection (green ellipses in Fig. 2). According to Ma and Morozov (2010), such variations of the gradient may be related to increasing pore pressures within the reservoir.

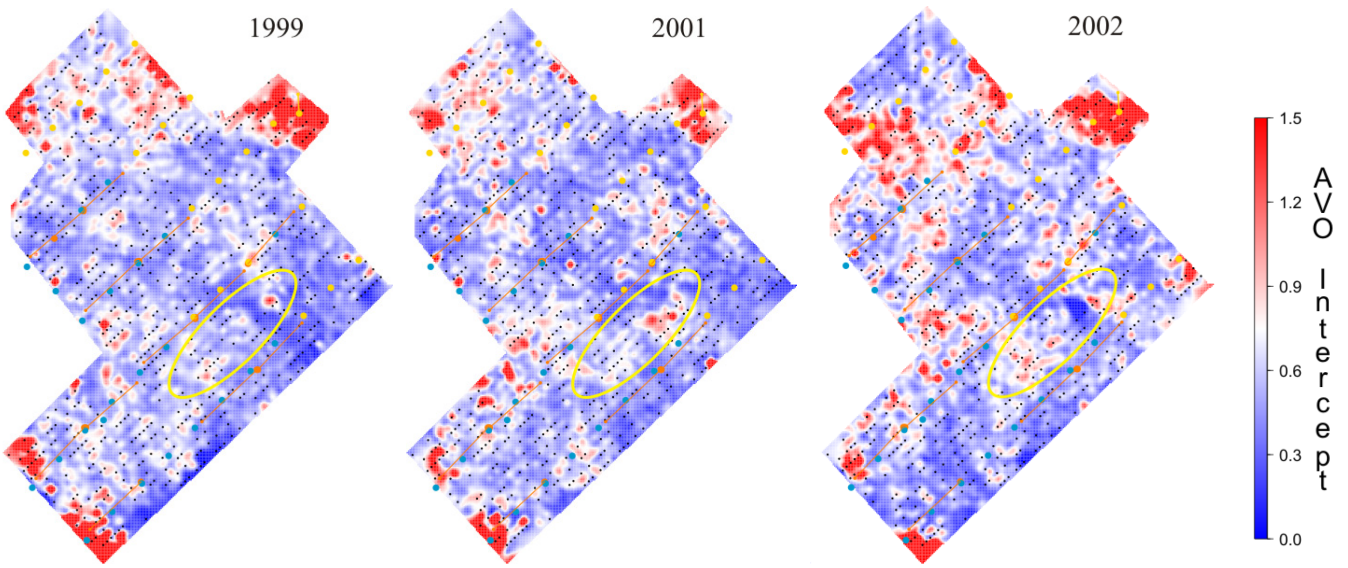

Figure 1: AVO intercept. Left: 1999; Middle: 2001; Right: 2002 Injection wells shown by brown color.

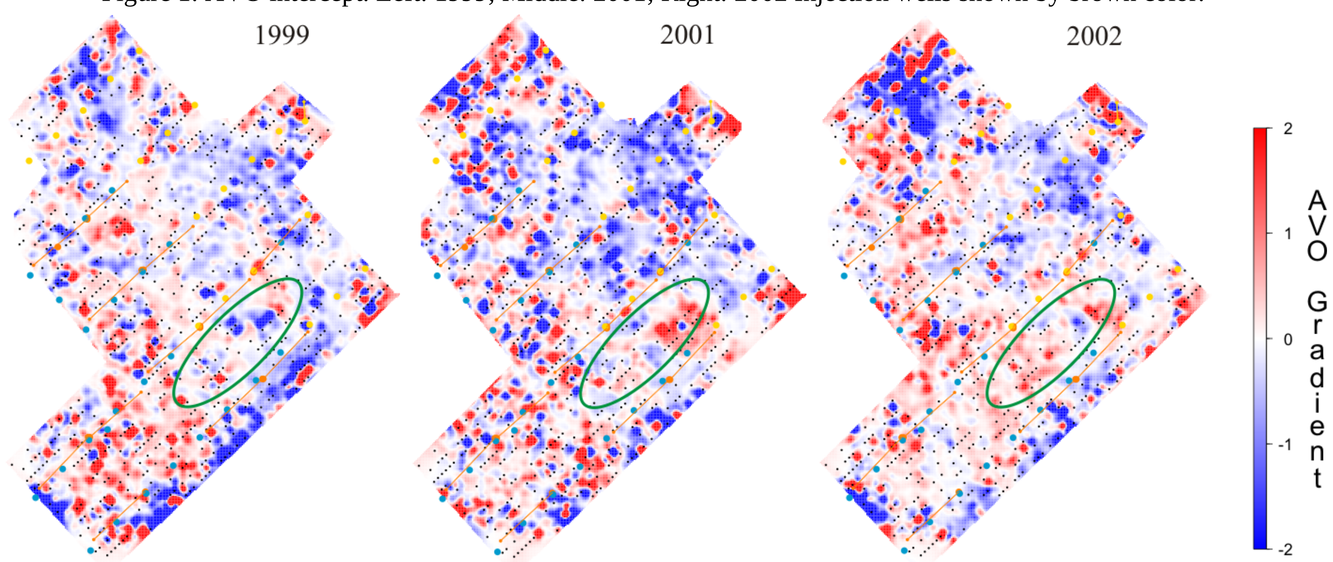

Figure 2: AVO gradient. Left: 1999; Middle: 2001; Right: 2002

Figure 3 shows the S-wave reflectivity derived from the AVO attributes for the same three years. The blue ellipses in these plots show that the S-wave reflectivity was also increased during injection, which may also be the evidence for CO_2 presence.

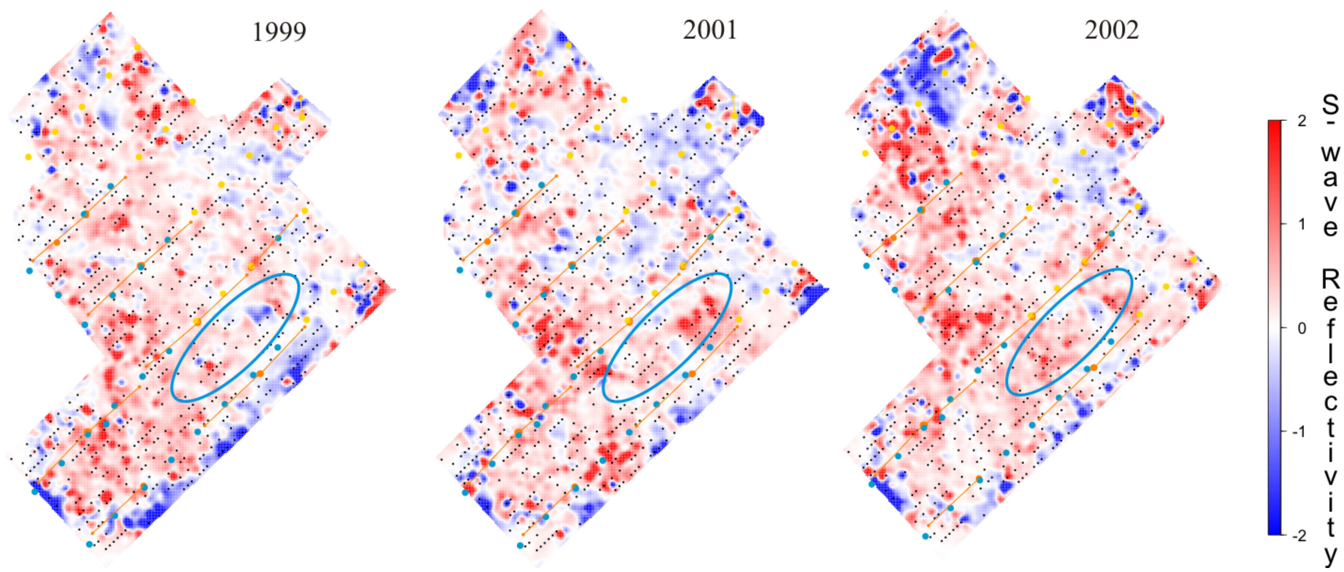

Figure 3: S-wave reflectivity. Left: 1999; Middle: 2001; Right: 2002. Injection wells shown in yellow..

Conclusions

Using the time-lapse AVO analysis, we examined the effects of saturation and pore-pressure changes. From Fig. 1, Fig. 2 and Fig. 3, in an area between the horizontal injection wells, the presence of CO_2 may be recognized by the increased variations in the measured AVO parameters. In further research, quantitative analysis should be focused on inverting these AVO attributes for variations of the pressure and CO_2 saturation.

Acknowledgements

The work is funded by Phase II of IEA GHG Weyburn CO_2 Storage and Monitoring Project.

References

Aki, K., and P. G. Richards, 2002, Quantitative seismology, 2nd ed.: University Science Books.

Ma, J., and Morozov, I. B., 2010, AVO Modeling of Pressure-saturation Effects in Weyburn CO2 Sequestration, The Leading Edge, 29, 178–183.

Ma, J., Gao, L., and Morozov, I. B., 2009, Time-Lapse Repeatability in 3C-3D Dataset from Weyburn CO_2 Sequestration Project, 2009 CSPG/CSEG/CWLS Convention.

Morozov, I. B., and Gao, L., 2009, Pre-stack Calibration of 3-C 3-D Time-Lapse Seismic Data, 2009 CSPG/CSEG/CWLS Convention.

White, D. 2009, Monitoring CO2 Storage during EOR at the Weyburn-Midale Field, The Leading Edge, 28, 838-842.

White, D. J., K. Hirsche, T. Davis, I. Hutcheon, R. Adair, G. Burrowes, S. Graham, R. Bencini, E. Majer, S. C. Maxwell, 2004, Theme 2: Prediction, Monitoring and Verification of CO_2 movements, *in* M. Wilson and M. Monea, eds., IEA GHG CO_2 Monitoring and Storage Project Summary Report 2000–2004, PTRC, Regina, 2004.

Zoeppritz, K. 1919, On the Reflection and Propagation of Seismic Waves. Erdbebenwellen VIIB, Gottinger Nachrichten. I, 66–84.