Time-lapse surface seismic monitoring of injected CO_2 at the Penn West CO_2-EOR site, Violet Grove, Alberta

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ABSTRACT

Results of time lapse analysis of repeated 2D and limited 3D seismic surveys at the Penn West CO_2-EOR site show very small changes between surveys. Data presented in this report show small changes in interval traveltime through the Cardium Formation reservoir. Investigation of seismic amplitude supports the observed changes in the traveltime and further suggests a possible directional flow of the injected $CO_{2.}$ The results are interpreted to indicate that the CO_2 is confined primarily to a thin interval within the reservoir and may be mappable using walkaway vertical seismic profile surveys. Further analysis, such as AVO, will be carried out in the future to delineate more information about the injected CO_2.

INTRODUCTION

Geological sequestration of carbon dioxide (CO_2), also known as carbon capture and storage in deep geological formations, is a technology that can be used for Enhanced Oil Recovery (EOR) and in reducing atmospheric greenhouse gases (GHGs) concentration at the same time. Thus, the drive for CO_2 geological sequestration is both economic and environmental. From economical perspective, CO_2 injection is suggested to enhance oil recovery to over 50% of the Original Oil In Place (OOIP) as compared to 10% from primary recovery and up to 30% from secondary recovery methods, like water-flooding and steam injection (Lake, 2006). This is certainly very important as demand for energy is at record high and projections suggest that the demand will continue to increase.

The feasibility of geological CO_2 sequestration technology has been studied by many (Herzog, 2002; USDOE, 2007) including the IPCC. A report on carbon capture and storage (IPCC, 2005) concludes that geological sequestration of CO_2 is feasible and probably is the best mean available for reducing post-combustion CO_2 concentration in the atmosphere. The technology has been implemented during the last decade, at different success levels, in different parts of the world including Canada (Davis at al., 2003), China (Yu et al., 2006), Norway (Arts et al., 2002) and the United States (Daley et al., 2005).

The Penn West site has been established by as a pilot study for CO2-EOR in Alberta. At the site, CO_2 has been injected into the Cardium reservoir since the commencement of the project in 2005. As part of the program, geophysical monitoring is being carried out by the means of time-lapse (2D and 3D) surface seismic and borehole Vertical Seismic Profiling (VSP) in an attempt to understand the CO_2 behavior within and around the reservoir and to evaluate the integrity of the storage (Lawton et al., 2005; Chen, 2006; Coueslan, 2007). The site has, also, been the subject of other (non-geophysical) monitoring, i.e. environmental (atmospheric and groundwater), geomechanical, geochemistry and pressure-temperature sampling.

This report gives an overview over the most recent time-lapse surface seismic data from Phase III (March 2007) in comparison to data from Phase II (December 2006) and Phase I (March 2005), more specifically in terms of P-wave interval traveltime and amplitude changes. Prior to presenting these results, an overview of geology of the study area is given. The report will conclude with some perspectives on future work.

STUDY AREA

The Violet Grove CO_2 injection site is located at the center of the Pembina Oil Field in the central plains of Alberta, about 120 kilometers southwest of Edmonton (Figure 1). The Pembina Field is the most aerially extensive oil field in the world, covering approximately 4000 km^2 (Dashtgard et al., 2006) with an estimated 7.4 billion barrels of OOIP with gravity ranging from about 40° API to greater than 45° API (Nielsen, 1984). Figure 2 shows an aerial photo of the area with the seismic base map overlaid. The figure, also, shows the location of the injection and the observation wells.

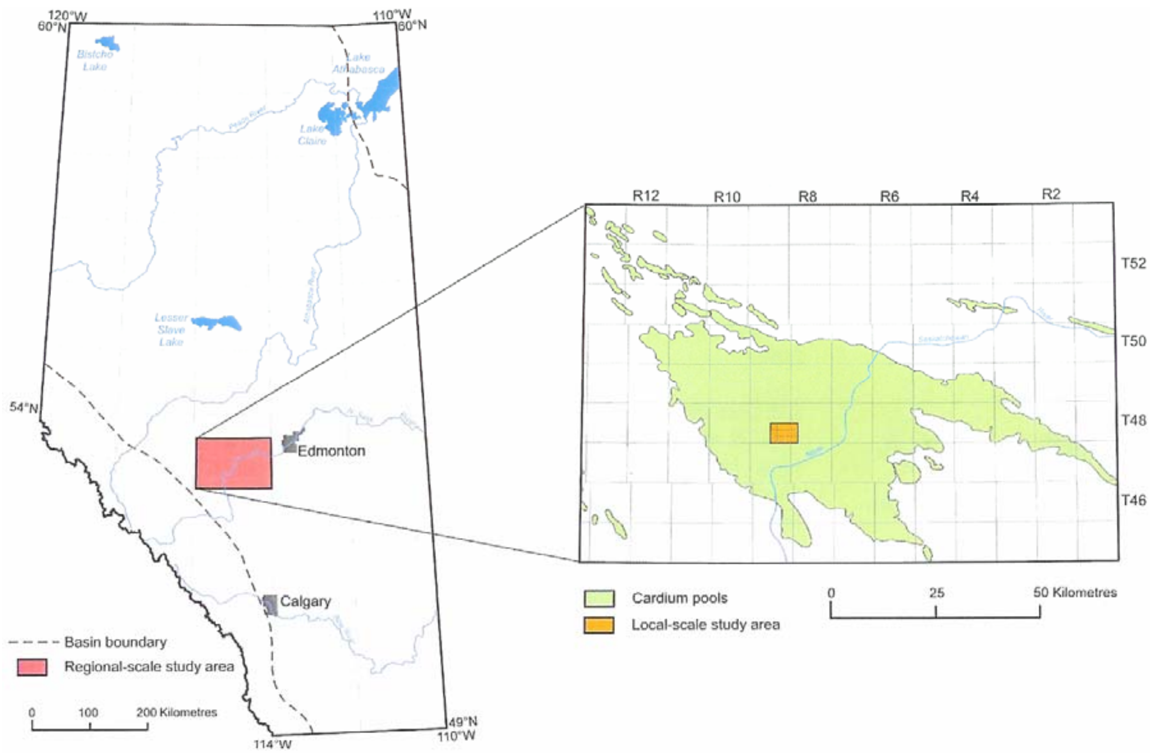


FIG. 1. Location map of the Pembina oil field. The study area is shown in orange rectangle (Dashtgard et al., 2006).

The most prominent reservoir unit within the Pembina field is the Cardium Formation, which was discovered in 1953 (Dashtgard et al., 2006). Plint et al. (1986) and Krause et al. (1994) define the Cardium Formation as "a clastic wedge that prograded into the western interior seaway during Turonian-Coniacian time. It is thickest in the foothills and thins to the east". The Cardium Formation was deposited during a relative change in sea level approximately 88.5 MA (Dashtgard et al., 2006). The formation is divided into two members: Cardium Zone Member and Pembina River Member (Figure 3). The Pembina River Member is subdivided into three sand subunits (upper, middle and lower), and three shale subunits (upper, middle and lower) (Figure 3). The Cardium Formation, which is Cretaceous in age, is bounded by the Wapiabi Formation on top and Blackstone Formation below; both are composed of thick shale sequences of the Colorado Group (Dashtgard et al., 2006).

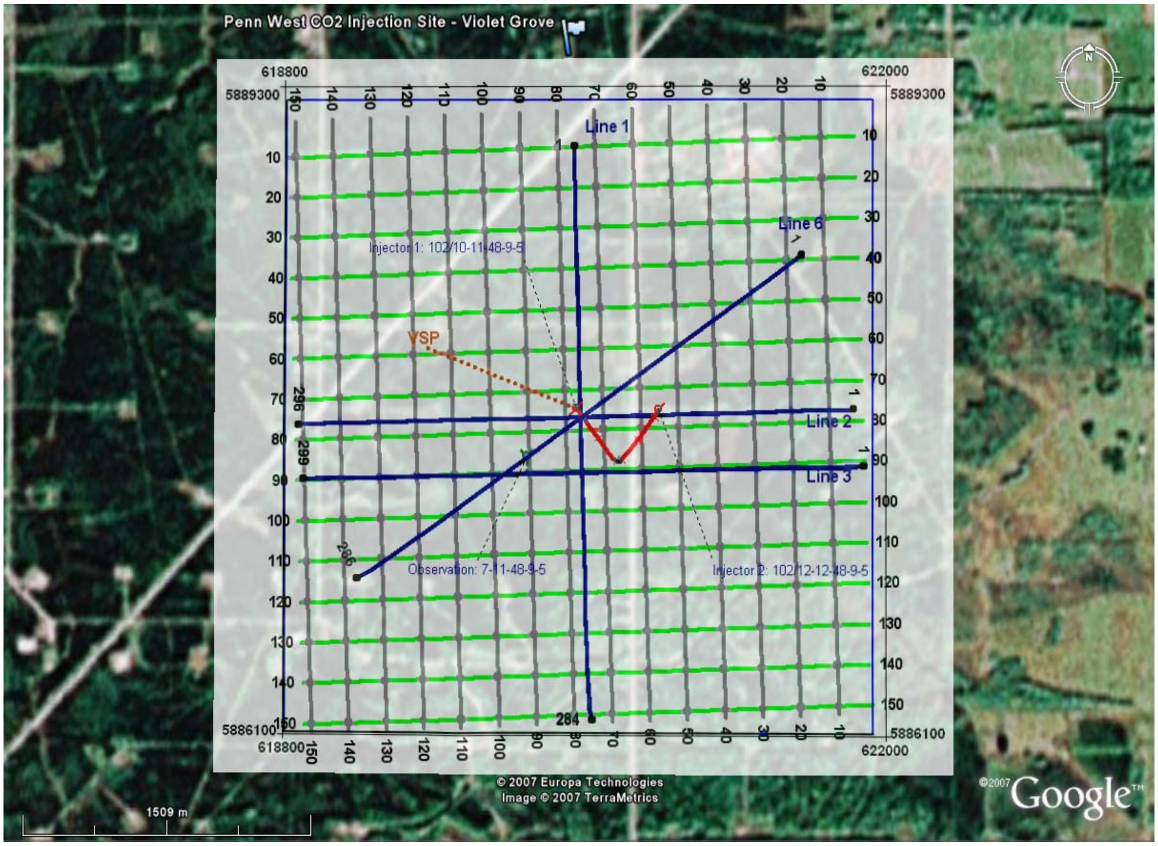


FIG. 2. Overview of the study area showing the seismic grid with locations of the 2D lines (dark blue) and the VSP (brown). The map, also, shows the injection and the observation wells. The map coordinates are UTMs (zone N11) with Northing along the vertical axis and Easting along the horizontal axis (aerial photo is courtesy of Google Earth®).

The Cardium reservoir is hosted within the upper sand of the Cardium Formation and varies in thickness between 0 to over 4 m across the study area. The Upper Sandstone is located directly below the erosive boundary with the conglomerate and is separated from the underlying Middle Sandstone by the zone of sandy shale up to 4 m thick (Figure 3) (Dashtgard et al., 2006). The thickness of the upper sand varies in the northwest-southeast direction and it dips toward the southwest (Dashtgard et al., 2006). Table 1 lists values of a number of physical properties of the Cardium reservoir (upper sand). Based on these values, CO_2 in a supercritical state is maintained at the reservoir conditions. Detailed description of the geology can be found in many publications, such as Patterson (1957), Plint et al. (1986), Krause et al. (1987, 1994), and Dashtgard et al. (2006).

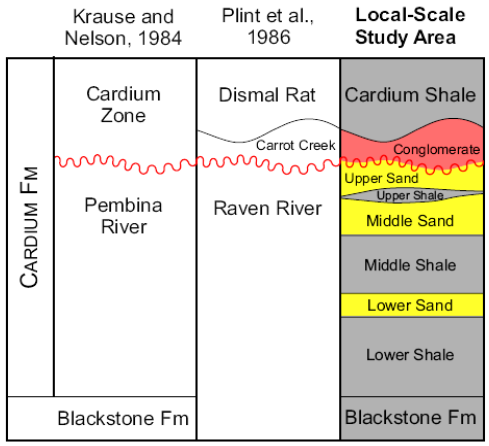


FIG. 3. Stratigraphic nomenclature of the Cardium Formation at the Pembina Field (Dashtgard et al., 2006).

Table 1. Values of some of the physical properties of the Cardium reservoir (upper sand) at the study area as estimated in Dashtgard et al. (2006).

Depth (m)	Thickness (m)	Pressure (MPa)	Temperature (C^o)	Porosity (%)	Permeability (md)
1650	**0 - 4**	**19**	**50**	**16.4**	**19.8**

METHODOLOGY

"Time-lapse seismology is based on repeating a seismic survey to determine the changes that have occurred in the intervening time, such as may be caused by production. Results are often displayed as difference sections or maps. When using multiple 3D surveys run at different times, this is sometimes called a 4D survey, the fourth dimension being the intervening time" (Sheriff, 1999). Observed changes assist in the characterization of the reservoir and the differences between the surveys may be attributed to changes in saturation, pressure and, in many fields, overburden stress due to reservoir compaction (Pickering, 2006).

Time-lapse surface seismic is an established tool in hydrocarbon reservoir monitoring (Sparkman, 1998; Meyer, 2001). The technique has been used for decades in monitoring hydrocarbon reservoirs through production and after water flooding or steam injection in Enhanced Oil Recovery (EOR) fields (Wang, 1997; Wang et al., 1998; Gabriels et al., 1999; Rogno et al., 1999, Meyer, 2001; Zweigel et al., 2001; Herawati, 2002; Davis et al., 2003; Lumley, 2004). Recent demands for solutions to the increasing atmospheric concentration of CO_2 have introduced this GHG into the "menu" of compounds being used in this enhanced recovery process. In non-economically driven projects, CO_2 is sequestered into deep geological formations for long-time storage. There are many studies in the literature that document the use of time-lapse surface seismic in monitoring CO_2 whether it is being used for enhanced recovery or if it being stored for pure environmental reasons (Chapman et al., 2000; Arts et al., 2002; Brown et al., 2002; Terrell et al., 2002; Li, 2003; Miller et al., 2004). The feasibility of such projects in

Alberta has been the scope of many studies (Krause and Collins, 1984; Bachu, 2000; Bachu et al., 2003; Bachu and Shaw, 2005).

The geophysical monitoring program at Penn West site is being undertaken by CREWES (Lawton, 2005; Lawton et al., 2005; Chen, 2006; Coueslan, 2007). The monitoring program consists of two components: active and passive geophysical monitoring. The scope of passive seismic monitoring is beyond the objective of this report. The following phases have been accomplished so far:

- Phase I: baseline multicomponent surface seismic survey, the objective of which was to image the Cardium reservoir before the CO_2 injection. The survey was acquired in March 2005 (Chen, 2006).

- Phase II: the first monitoring survey after the CO_2 injection (December 2005). The primary objectives were to detect the CO_2 plume, identify any CO_2 leakage and delineate possible changes within the reservoir.

- Phase III: the second monitoring survey (March 2007). In this phase, a new 2D seismic line was added into the program. An additional goal to the main objectives sought in Phase II, was to determine if surface seismic data can provide direct detection of the CO_2 plume in the study area. In order to achieve these objectives, high resolution 16-level VSP survey was simultaneously acquired in addition to the surface seismic in order to provide improved image of the target.

Even though multicomponent (3C) time-lapse surface and Vertical Seismic Profiling datasets were acquired as well, this report addresses only some of the results from the P-P time-lapse surface seismic surveys. The results presented in this report are based on analyzing P-P interval traveltime differences between several horizons: Ardley, Lea Park and Viking Fm from the three surveys (Phase I, II and III). The Ardley Formation is a shallow coal of Lower Tertiary age that is a prominent seismic reflector; the Viking Formation is a sandstone unit that generates a high amplitude reflection at later times than the Cardium event. Changes in the amplitude of the Cardium horizon were also examined. The main software used in performing the analysis were Vista® and Kingdom Suite® packages.

The time-lapse surface seismic data at Violet Grove were acquired and processed by Veritas DGC. The datasets from the three phases (I, II and III) were acquired and processed in a consistent manner in order not to compromise the subsequent time-lapse analysis and interpretation. Even though it is difficult, if not impossible, to eliminate all the acquisition and processing limitations inherited within time-lapse seismic data, every effort was put in this study so that the effects of these limitations are minimal. For instance, all the 2D and 3D seismic surveys were designed in such a way to maximize the coverage near the main injection (injector 1) and the observation wells. The 3D dataset and the individual 2D lines were fold-matched. The datasets were processed using the same processing flow and parameters, when appropriate. Finally, a shaping filter was applied to minimize differences between the processed datasets over time windows earlier than the Cardium event.

RESULTS AND DISCUSSION

Phase I and II surveys were conducted through the acquisition of two east-west parallel 2D seismic lines, about 250 m apart, and an orthogonal north-south 2D line (Figure 2). Line 6 was added in Phase III in an attempt to directly image the CO_2 plume in the southwest-northeast direction. All lines were live for all shots of the survey. Figure 4 shows snapshots of the fold of the surface seismic data at different inline locations. The figure illustrates how the fold of the seismic data varies across the surveyed area as portions of the subsurface will have more weight in the imaging process than others (i.e along the 2D lines vs between them). This limitation was mitigated, when possible, by maximizing the coverage near the injection (injector 1) and observation wells around the middle of the study area by adding 2D receiver lines as well as the VSP dataset (Figure 2).

Figure 5 (a) and (b) show displays of Line 1 from the baseline survey (Phase I) and the second monitoring survey (Phase III), respectively. The difference between the two is demonstrated in Figure 6 (a) and (b), where Phase I is subtracted from Phase III. In this example, it seems that there is not a significant variation between Phase I and Phase III expect for noise and migration artifacts. Figure 7 is a graph of the change in the Ardley to Viking isochron, i.e. interval traveltime, between the Phase I and Phase III surveys. By analyzing the diagram, more specifically around trace 126, one can observe a slight increase in the Ardley-Viking interval traveltime in the order of 1 ms. This change in traveltime is consistent with that predicted by Chen (2006). Similar results were observed when performing the same analysis on Line 2 and Line 3 (Line 6 did not have a baseline survey). The apparent lack of anomalies in this type of analysis indicates that the 2D surface seismic data may not be able to detect the differences between the various phases from an imaging perspective, and it indicates that we need to carry out more sophisticated analyses, e.g. amplitude variation with offset (AVO), to reveal the subtle variations caused by the CO_2 plume. Furthermore, we probably need to use high resolution VSP data as increased bandwidth in VSP data acquired in Phase III, compared with surface seismic data may reveal small changes near the injection well (injector 1). Figure 8 shows the tie between surface seismic data and a corridor stack from a zero-offset VSP survey along Line 1. The Cardium Fm event is clearly identifiable in the VSP data, but not in the surface seismic data.

Figure 9 shows 3D visualization of the four horizons picked in the analysis, namely the Ardley, Lea Park, Cardium, and Viking Formations. Figure 10 displays amplitude analysis of the Cardium horizons for the three survey phases. Arguably, there is a small increase in the amplitude near the injection well (injector 1). It is also possible to observe the subtle and isolated amplitude increase inside the green circle in the amplitude difference maps in Figure 11. The amplitude change is also reflected on the Viking horizon, illustrated in Figure 12. The reduction in the amplitude in the middle of the horizon could be due to the CO_2 plume or simply a processing artifact. In general, the amplitude variations in Figures 10-12 may be attributed to the CO_2 plume among other things like water flooding prior to the CO_2 injection. Another consideration is that the reservoir is dynamic, e.g. it is still producing.

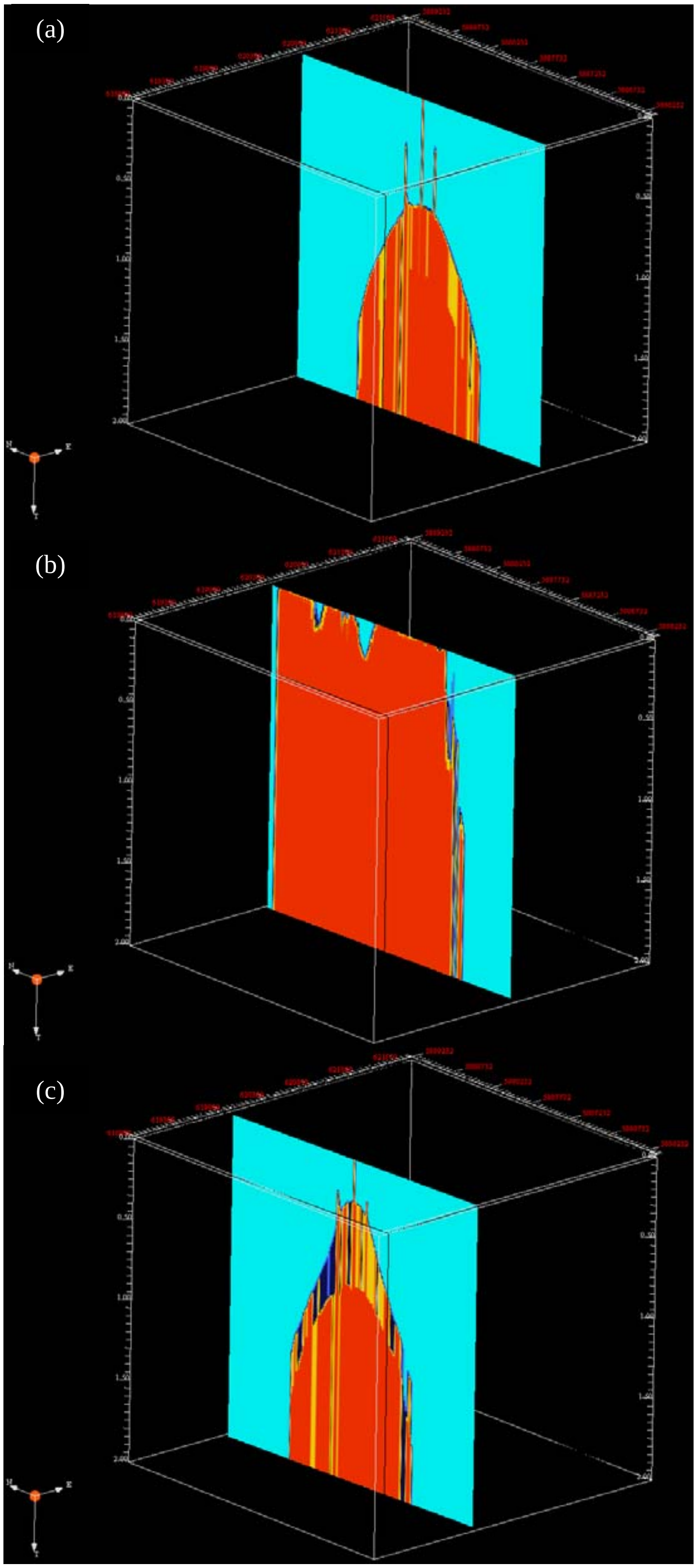
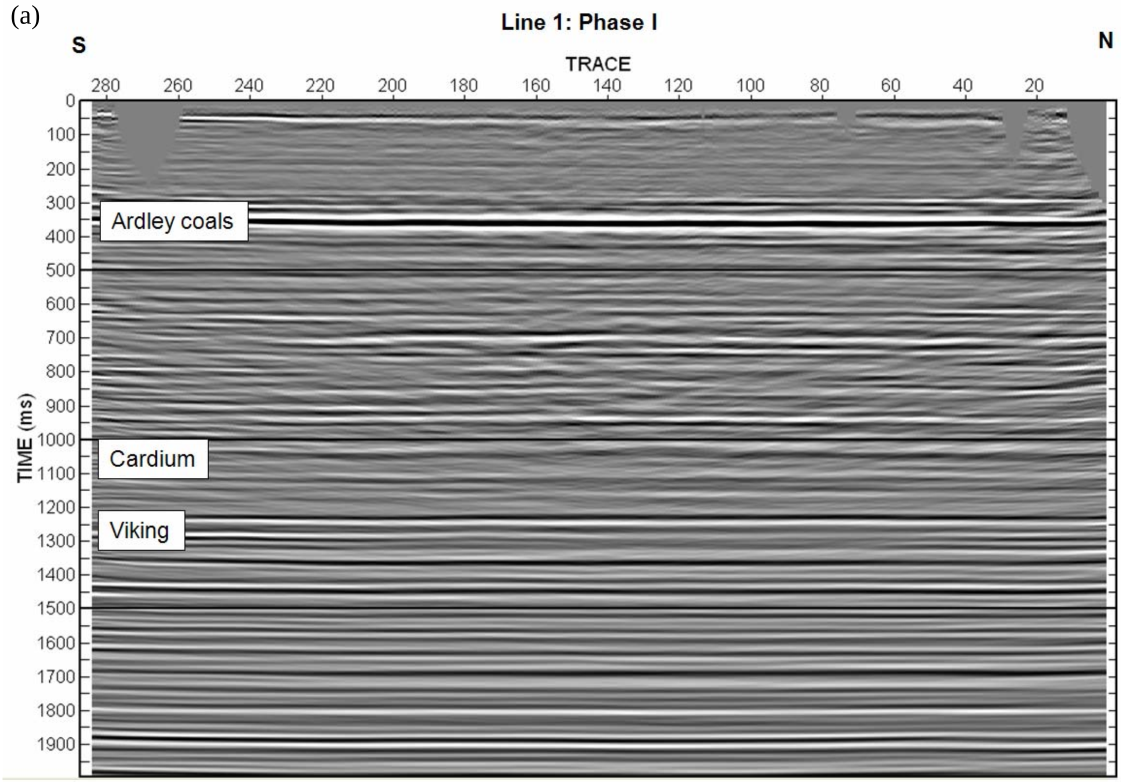


FIG. 4. Snapshots of the fold of the surface seismic data at the Penn West site: (a) inline 58, (b) inline 77 and (c) inline 100. Red color indicates high fold (60) whereas turquoise indicates low fold (0).

(a)



(b)

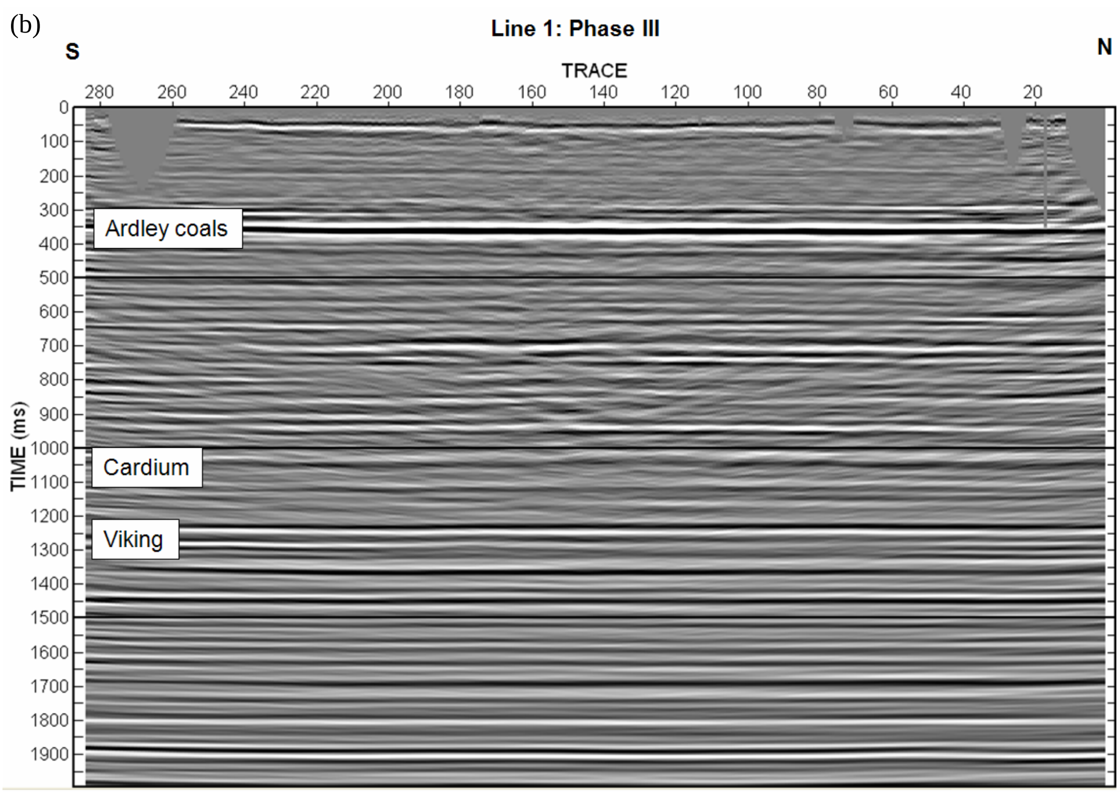


FIG. 5. Displays of Line 1 from: (a) the baseline survey (Phase I) and (b) the 2nd monitoring survey (Phase III).

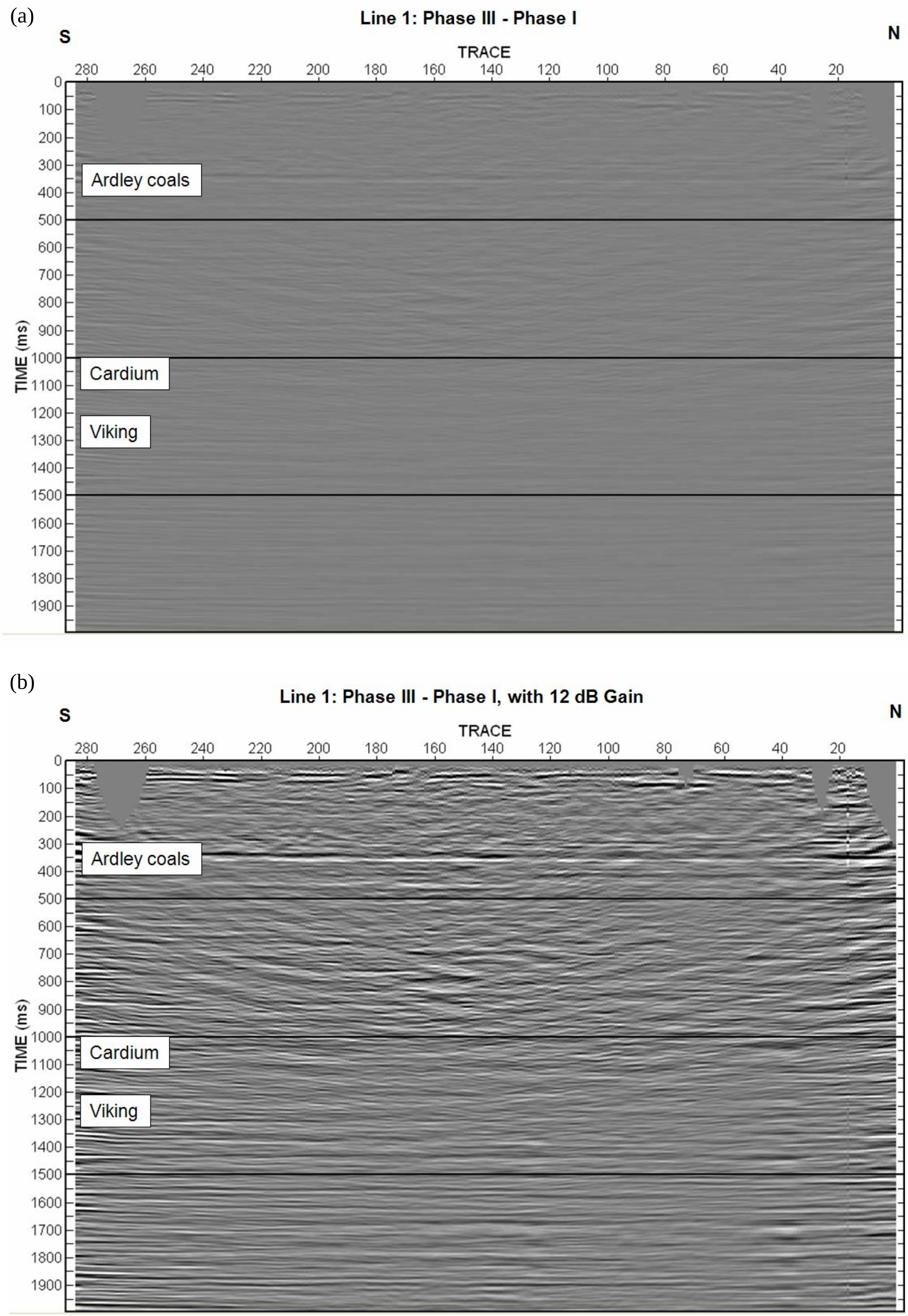


FIG. 6. The difference in Line 1 between Phase III and Phase I before (a) and after (b) applying 12 dB gain.

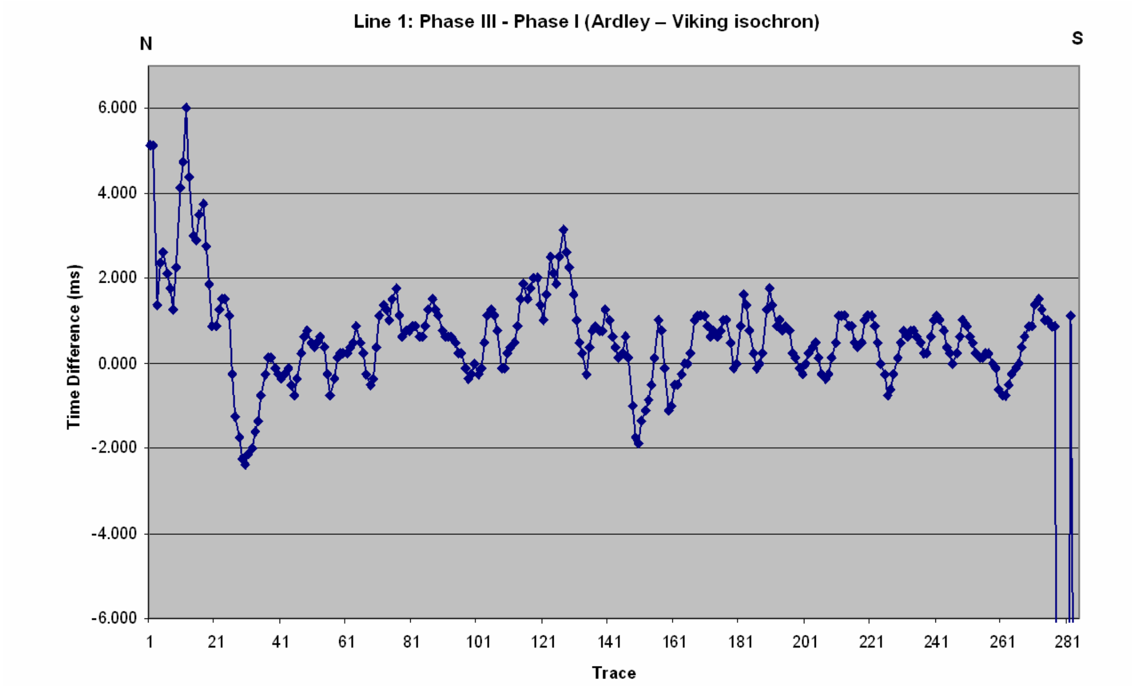


FIG. 7. The difference in the interval traveltime (isochron) between the Ardley and Viking horizons between Phase I and Phase III (Line 1). Notice the increase in the interval traveltime near trace 126.

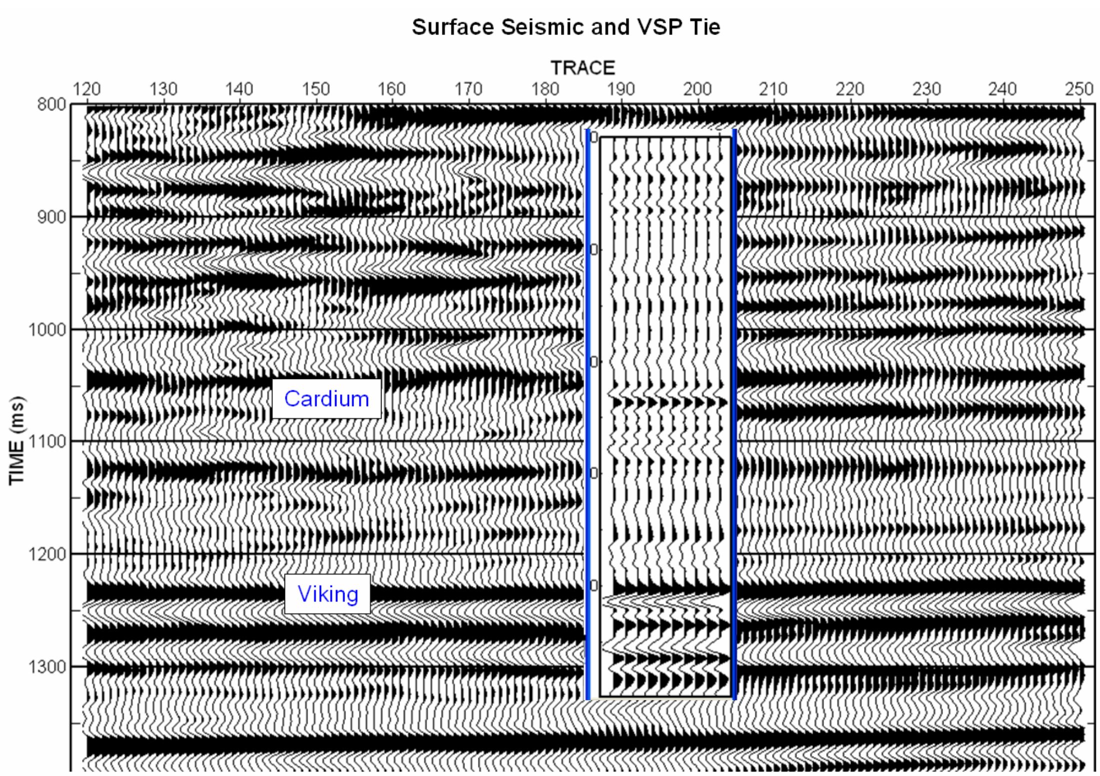


FIG. 8. Tie between surface seismic and VSP. Notice the better resolution capabilities of the VSP compared to surface seismic.

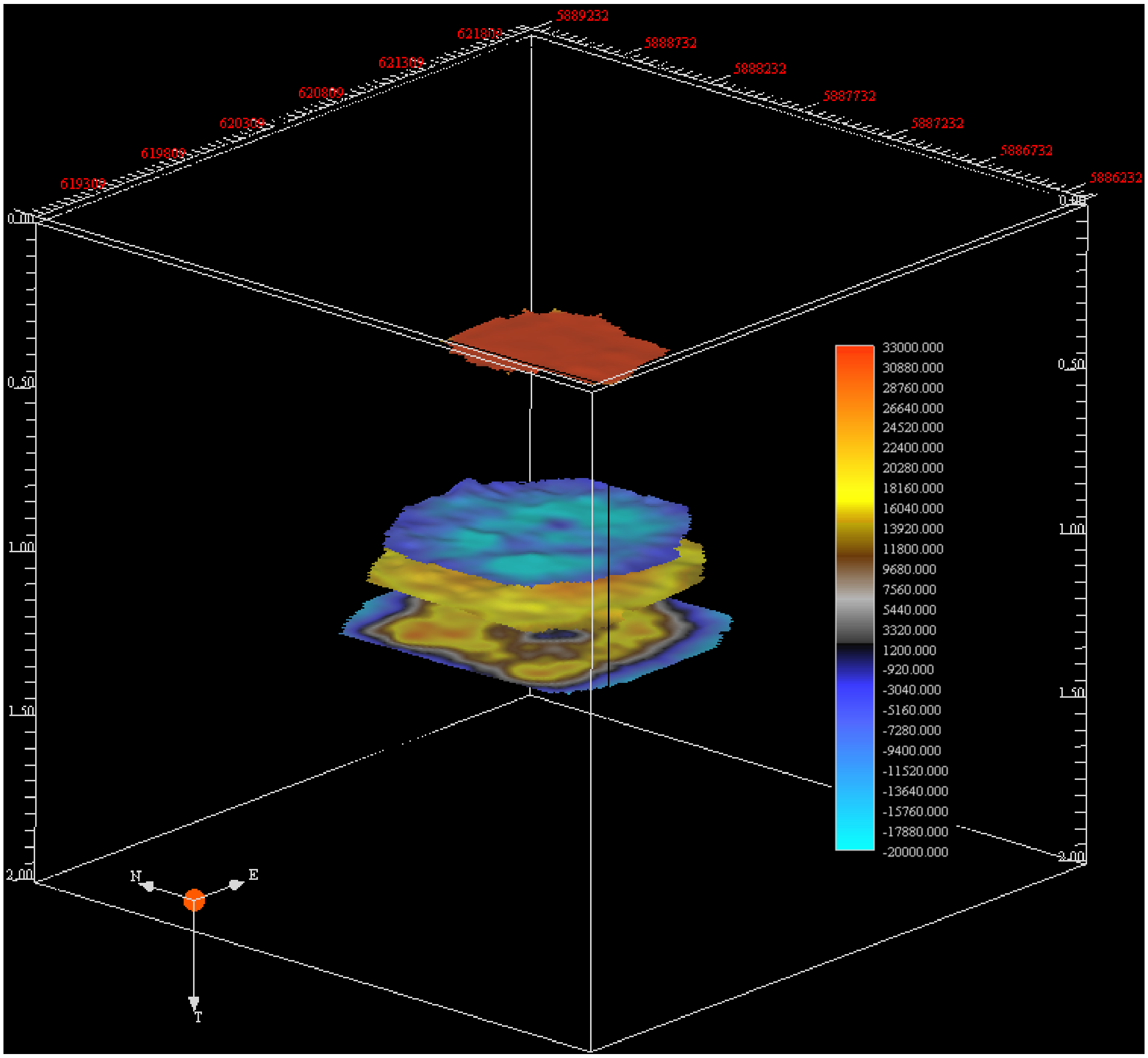


FIG. 9. Visualization of the various horizons (amplitude) used in the analysis. From top to bottom: Ardley (t ≈ 0.366 s), Lea Park (t ≈ 0.936), Cardium (t ≈ 1.044 s), and Viking (t ≈ 1.23 s), where t is the two-way traveltime.

The Ardley and the Lea Park horizons are two prominent events in the 2D and 3D seismic data and since they occur shallower than the Cardium event in the seismic volume, they can be utilized, in conjunction with events at times later than the Cardium event, to quantify any time delay that results from the CO_2 plume. This can be achieved by calculating the change in the interval traveltime between the Ardley-Viking and Lea Park-Viking events since the Viking horizon occurs deeper in the seismic volume, as illustrated in Figure 9. The results are shown in Figures 13 and 14. Similar manner to the pattern observed in the 2D data (Figures 6 and 7), there is subtle increase in the interval traveltime between Ardley-Viking and Lea Park-Viking in the order of 1 ms. The greatest interval traveltime increase, near injector 1, is observed in the difference between Phase I and Phase III in Figure 13 (a) and Figure 14 (b) due to the larger volume of injected CO_2 between March 2005 and March 2007. Finally, changes in amplitude and interval traveltime seem to be in agreement with geochemical sampling at the observation well. However, it is difficult to draw solid conclusions at this point.

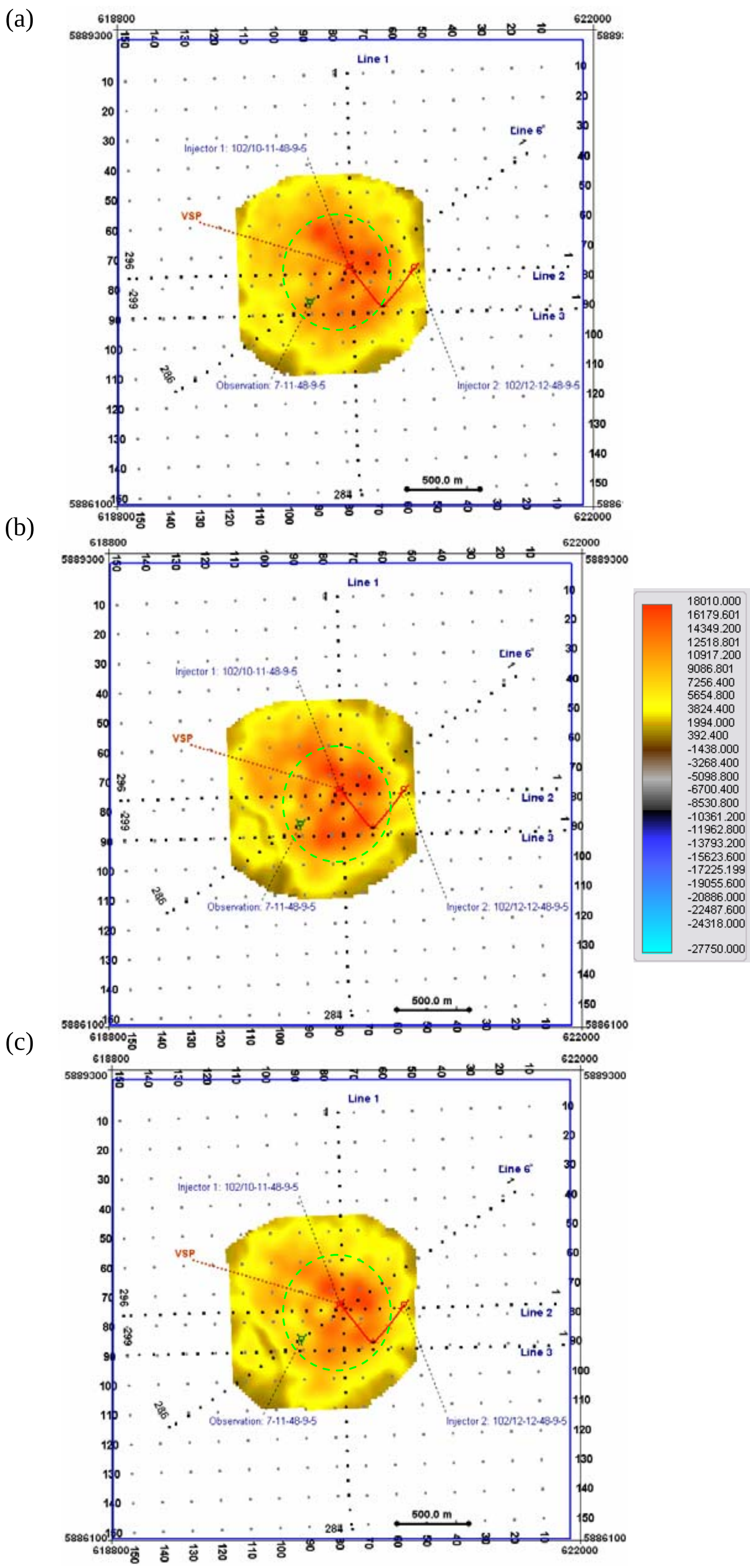


FIG. 10. The Cardium horizon amplitude (scale bar) from: (a) the baseline survey (Phase 1), (b) the 1st monitoring survey (Phase II), and (c) the 2nd monitoring survey (Phase III). Vertical scale is Northing and the horizontal scale is Easting in meters.

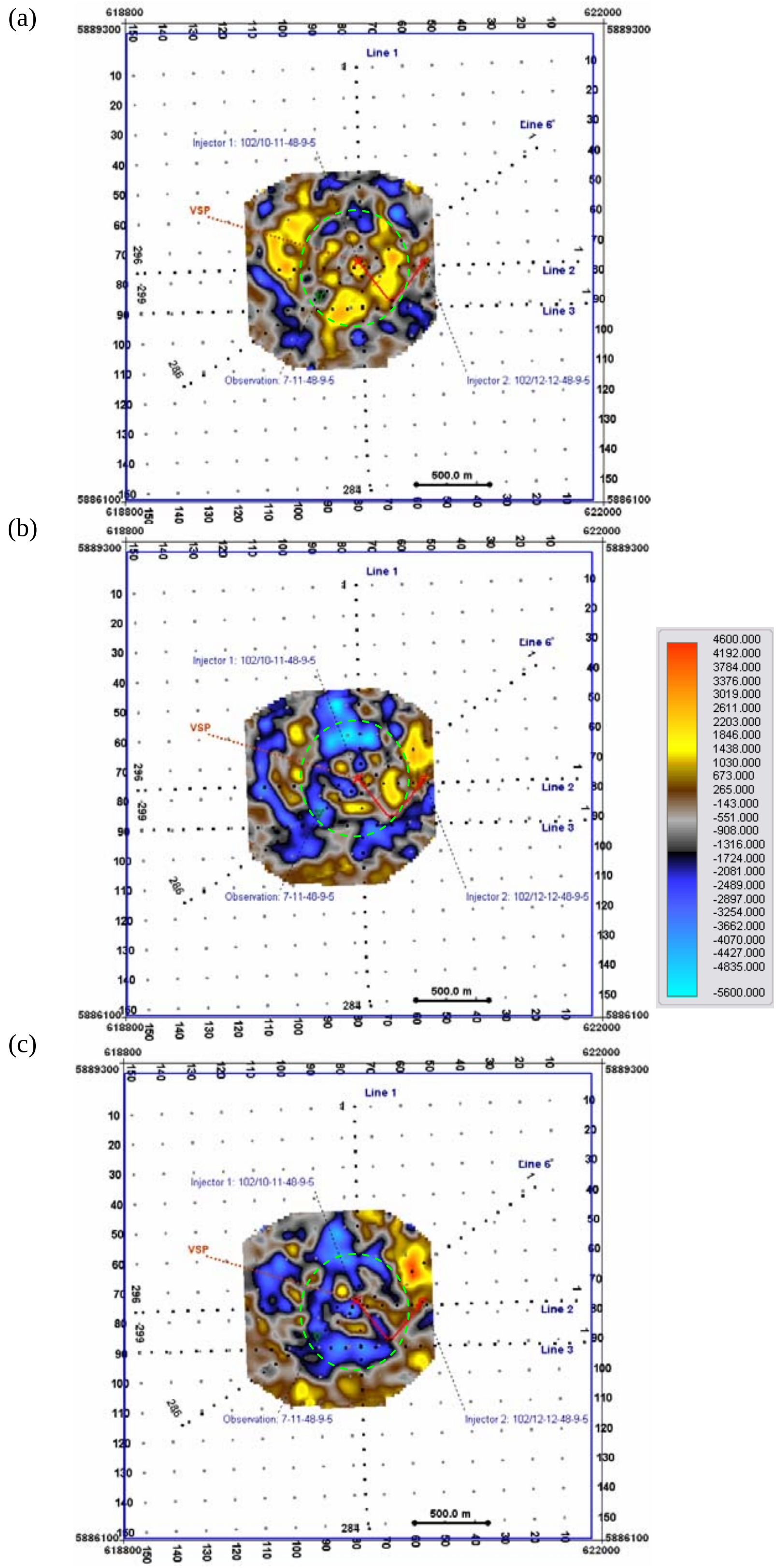


FIG. 11. The difference in the Cardium horizon amplitude (scale bar) between: (a) Phase II and Phase I, (b) Phase III and Phase I, and (c) Phase III and Phase II.

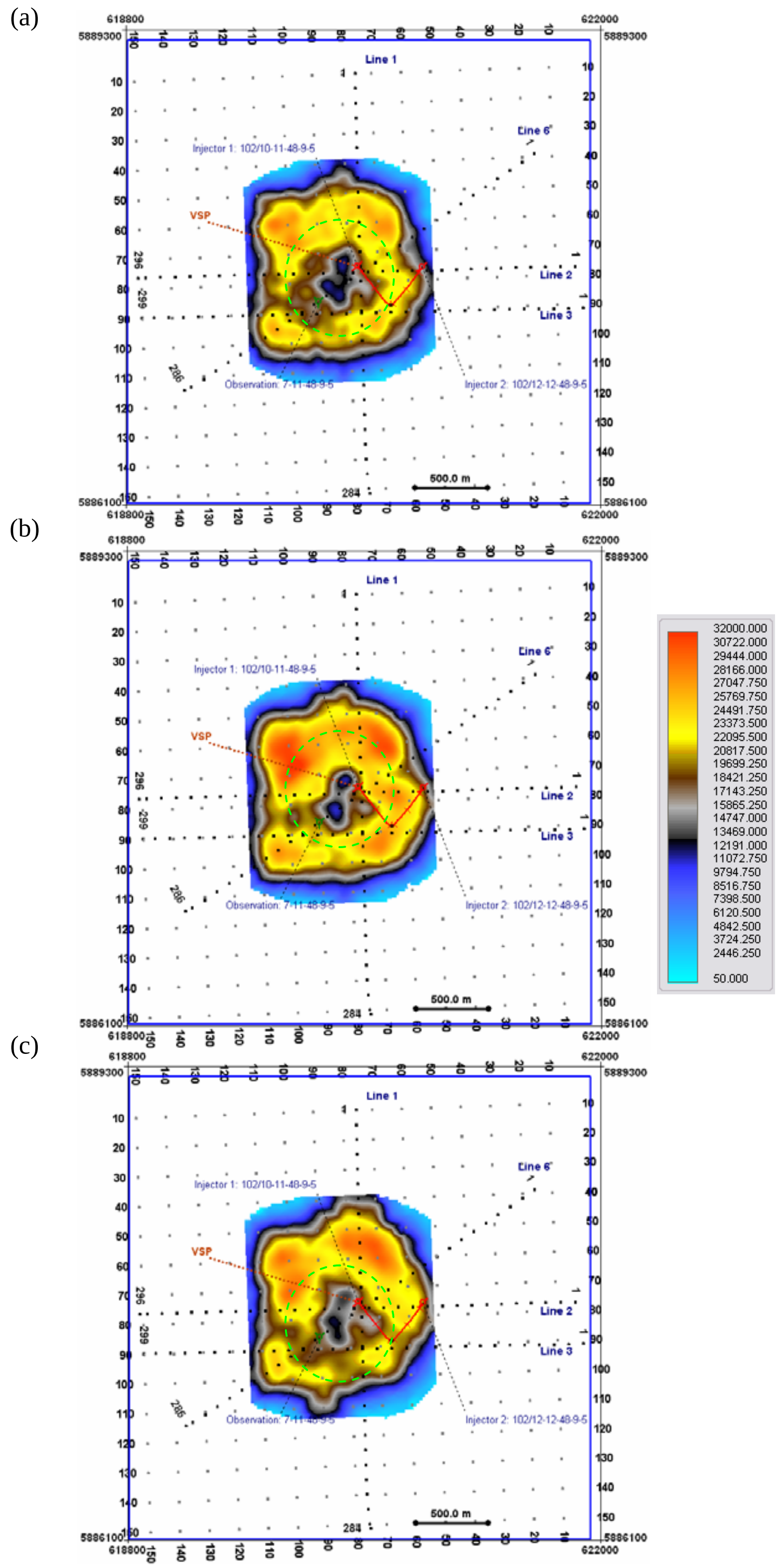


FIG. 12. The Viking horizon amplitude (scale bar) from: (a) the baseline survey (Phase 1), (b) the first monitoring survey (Phase II), (c) and the second monitoring survey (Phase III).

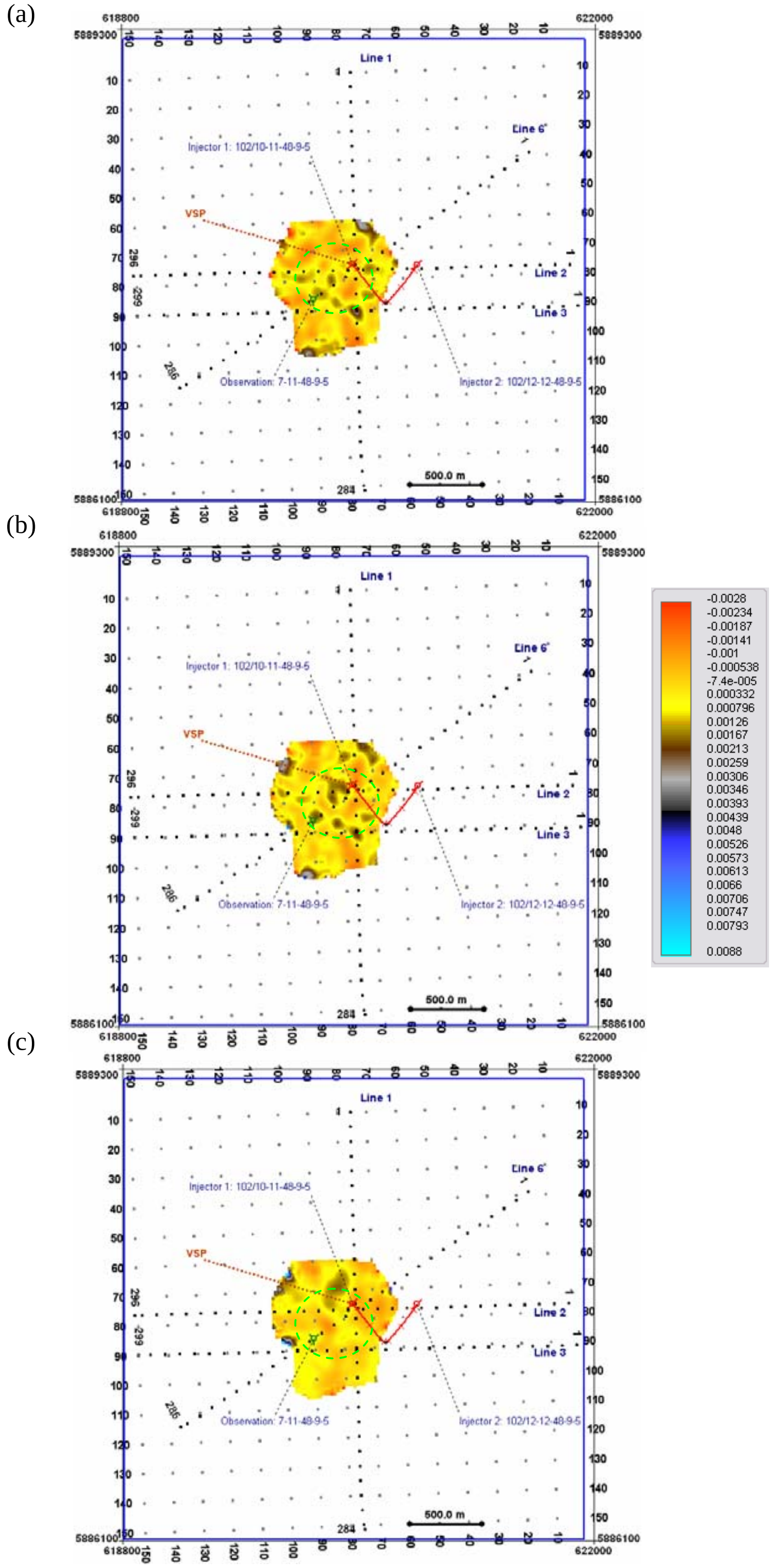


FIG. 13. The interval traveltime difference (scale bar in seconds) between the Ardley and the Viking horizons: (a) Phase II - Phase I, (b) Phase III - Phase I, and (c) Phase III - Phase II.

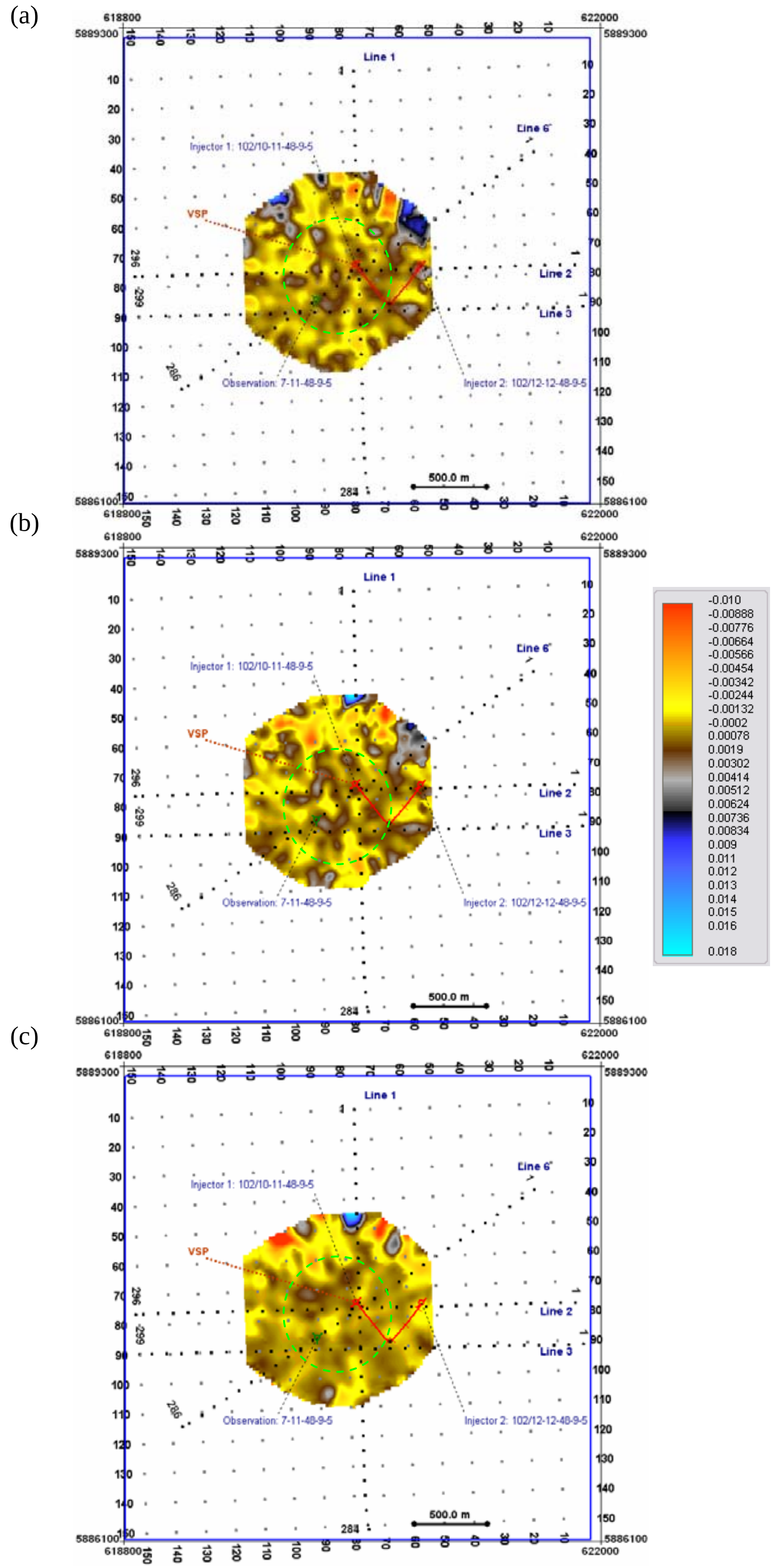


FIG. 14. The interval traveltime difference (scale bar in seconds) between the Lea Park and the Viking horizons: (a) Phase II – Phase I, (b) Phase III - Phase I, and (c) Phase III – Phase II.

CONCLUSIONS

Time-lapse surface seismic analysis shows subtle variations in the amplitude of the Cardium horizon between surveys, which might suggest that the reservoir is responding to the injected CO_2. Furthermore, the changes in the interval traveltime (e.g. slight pull-down effect) as observed in the time-lapse surface seismic datasets seems to be in agreement with what is expected after CO_2 is injected into oil reservoirs. Ongoing work will involve looking into the multicomponent VSP as well as the P-S component of the surface seismic data. In addition to the traveltime and amplitude, we will look into other seismic attributes, such as velocity and impedance. Integration of geochemistry information into the analysis is also considered.

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