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Carbon dioxide volume estimated from seismic data after six years of injection in the oil field of Buracica, Bahia

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Abstract

Carbon dioxide has been injected since 1991 in the oil field of Buracica in the Recôncavo Basin in Brazil for EOR purposes. The CO_2 gas is injected into the upper oil reservoirs, a 13 m-thick sandstone layer, at a depth of about 550 m. The reservoir is included in a tilted block dipping at an angle of 5 to 6° toward the south-east.

A 3D seismic survey was carried out six years after the beginning of CO_2 injection. Sensitivity studies concluded that the gas-invaded and the oil-filled parts of the reservoir show only a weak contrast between their mechanical properties so that their interface might not appear in the seismic sections.

Directional dip filtering of the seismic data underlines horizontal events crossing the dipping layer interfaces. Some of them can be interpreted as the gas/oil contact. A careful picking and mapping of these events reveal two accumulations of carbon dioxide on each side of a system of N-S faults, with slightly different gas/oil contact levels. Estimation of the gas volume and of the density leads to a rough estimate of the mass of CO_2 in place, indicating that about one third of the CO_2 injected was stored in the reservoir.

CO_2 storage; monitoring

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Introduction

A large cooperation project was initiated by Petrobras and IFP in 2007 about CO_2 capture and storage in the Recôncavo Basin. Petrobras has been injecting carbon dioxide in the oil field of Buracica since May 1991 (Rocha et al, 2007). 3D seismic data were acquired at Buracica in September 1997, six years after the beginning of CO_2 injection.

Because of the thinness of the reservoir and of low velocity contrasts between sandstones and shales at the reservoir's depth, the CO_2/oil contact cannot be detected in the raw seismic sections. The main questions addressed in this paper are to locate the CO_2 plume at depth and to estimate the volume occupied by CO_2 at the time of the seismic data acquisition.

Buracica Field – Geology and lithology

The main oil reservoirs are in the Sergi Formation, which consists of sandstones with some argillaceous intercalations, separating 14 reservoir units over a depth of 200 m.

On the Buracica Field, the Sergi Formation is divided into three main tilted blocks, separated by faults. In the central block, the Sergi Formation and the Itaparica sealing shales have a general dip of 5 to 6° south-eastward (Fig. 1).

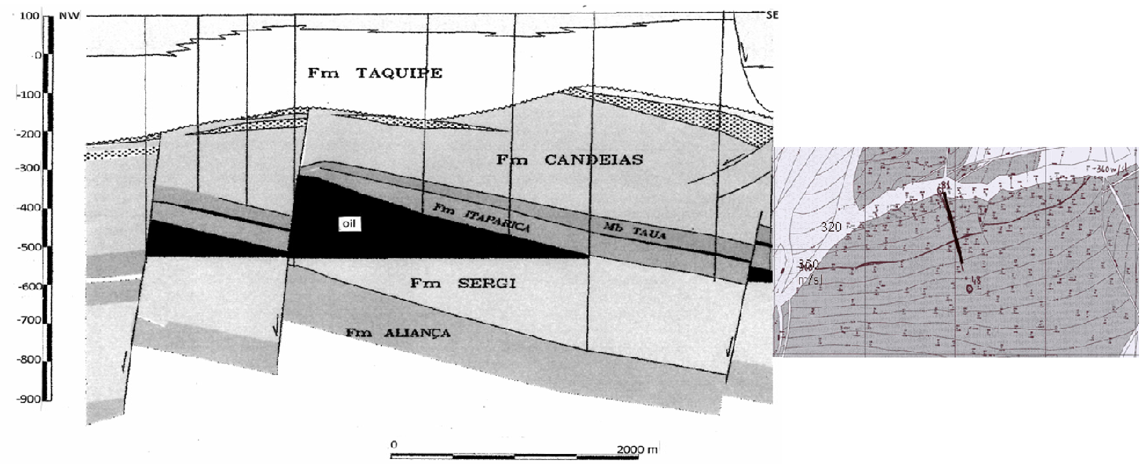

Figure 1. North-South geological cross-section (left) and structural map (right) of the Buracica field. The location of the cross-section is marked by a line on the structural map.

The top reservoir where CO_2 is injected, Sergi I, is made of wind deposits and shows a good lateral continuity. It has an average thickness of 13 m and an average porosity of 22%. Reservoir Sergi I is separated from the reservoir located right below it by a few metres of hardened shaly paleoground (Schinelli, 2002). The top reservoir is sealed by a hundred metres of shales of the Itaparica Formation. The underlying reservoirs are made of fluvial deposits and show numerous superimposed meandering channels, with a general flow direction from northwest to southeast.

Well logs, synthetic seismic traces and gas/oil contact modelling

Close to the northern fault, well 384D reaches the top of the Sergi I reservoir at 520.5 m depth (319 m below sea level). At that depth, the reservoir is invaded by the injected CO_2, as confirmed by the decrease in "neutron porosity" between 521 and 528 m depth. The top of the second reservoir was encountered at 335.7 m below sea level. The P-wave velocity is close to 3000 m/s between 521 and 528 m depth and close to the velocity in the sealing shales. The density, however, falls from about 2.45 g/cm^3 in the shaly seal to about 2.22 g/cm^3 in the Sergi I reservoir, filled with CO_2.

Acoustic impedances are the products of the density by the P-wave velocity. Reflection coefficients are the relative differences of the acoustic impedances between two samples. These quantities can be computed from the sonic and density logs. A synthetic seismic trace is then obtained by convolving the series of reflection coefficients by a wavelet having about the same frequency spectrum as that of the data. Convolution was performed with symmetric and anti-symmetric wavelets. An anti-symmetric wavelet having a 40 Hz central frequency provided the best fit between the synthetic traces and the stacked section, as shown in Figure 2 when comparing columns 6 and 7.

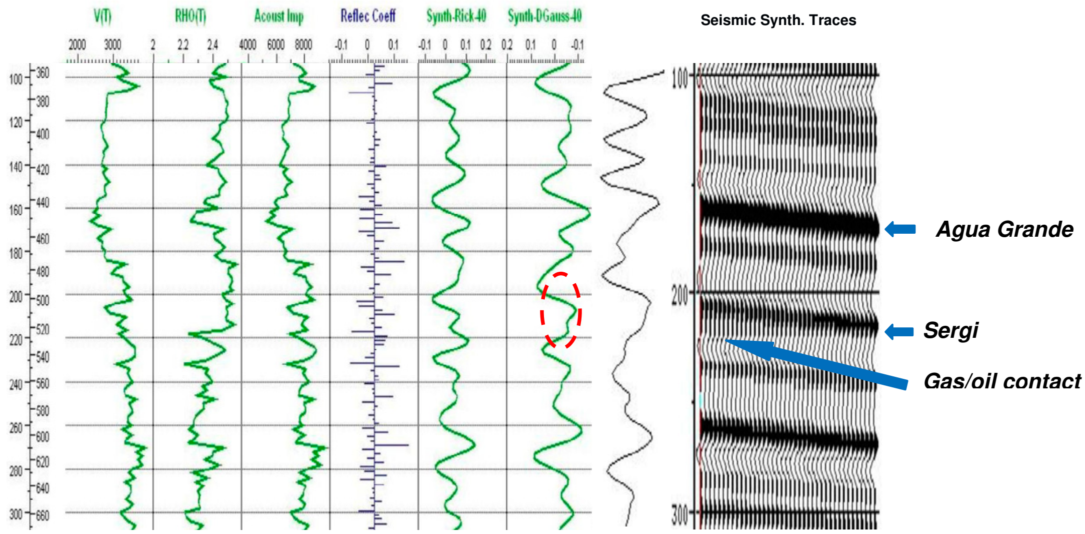

Figure 2. From left to right: P-wave velocities, densities, acoustic impedances, reflection coefficients, synthetic traces obtained with symmetric and antisymmetric wavelets and the real seismic trace extracted from the 3D stacked data at the well 384D location. The panel on the right is a synthetic seismic section for a model of gas/oil contact.

The synthetic waveforms show a large peak at the Agua Grande level (160 ms), followed by a wide and large trough and another peak at the top of the Sergi Formation (200 ms). The presence of carbon dioxide reveals itself through a slight indentation of the positive arch corresponding to Sergi I's level (Fig. 2, around 210 ms, red circle).

We simulated the seismic response of the gas/oil contact by using the P-wave velocity and density logs of well 384D, where gas is present between depths of 522.8 and 527.8 m. Virtual logs were derived by progressively shifting the logs vertically to simulate information that would have been recorded at several locations spaced 1.5 m apart along the horizontal direction over the layered block dipping at 6°. The gas/oil contact was modelled by replacing the density and velocity by oil-filled sandstone characteristics below 528.5 m. Acoustic impedances and reflection coefficients were computed for each vertical shift. The reflection coefficients were convolved with the 40 Hz central frequency asymmetrical wavelet, giving the synthetic section shown on the right-hand side of Figure 2. At the left of this section, where the reservoir is filled with gas, the reflection on Sergi's top is marked by an asymmetrical positive peak (200-220 ms); at the right, where the reservoir is filled with oil, the positive peak narrows and is followed by a large trough. In between, where the reservoir is filled by gas at the top and by oil at the bottom, the horizontal gas/oil contact is revealed by a horizontal zero amplitude line at 220 ms.

The question now raises if such features can be detected in the 3D seismic data block acquired in 1997. Horizontal events can be observed in some sections of the 3D block (e.g. in the left panel of Fig. 3 around 364 ms). Directional dip filtering was performed to enhance the events contained within a given dip angle range and to attenuate all other events. The filtered sections show several more or less horizontal events indicated by arrows in the right-hand side panel of Figure 3.

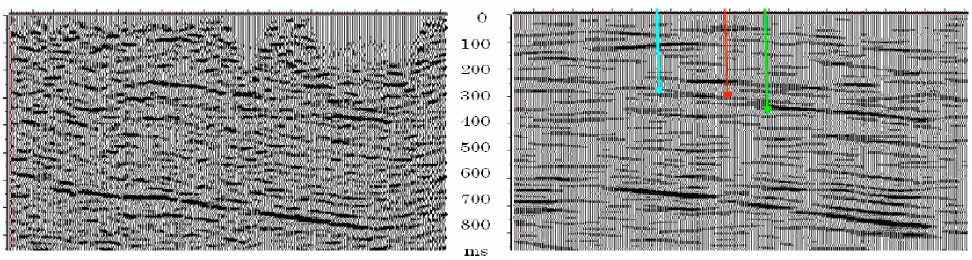

Figure 3. A North-South inline seismic section unfiltered (left) and directionally filtered (right).

Channels – Quasi-horizontal feature at 364 milliseconds

The faint horizontal event seen in the left section of Figure 3 at 364 ms is much better displayed in the right section of Figure 3 where it is marked by a green arrow. This event extends considerably in the inline direction with some slight undulations below the reflection originating from the top of the Sergi Formation. The channelling character of this event is confirmed by crossline sections, where the curved bottom of a channel is visible under a quasi-horizontal reflection associated with the sedimentary fill of the channel (Fig. 4, left panel, green ellipse).

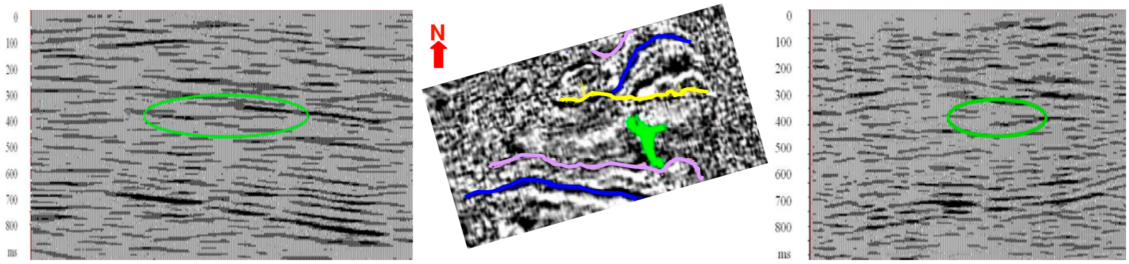

Figure 4: 3D FK-filtered North-South inline section (left), time slice extracted from the 3D seismic data cube at 364 ms (middle) and 3D FK-filtered West-East crossline section (right). The yellow line marks the location of the West–East main fault, the dark blue line corresponds to the Agua Grande reflection, the purple line represents the Sergi horizon and the green area is the channel interpretation.

In addition to displaying the seismic amplitudes at 364 ms, the time slice presented in Figure 4 also shows in green colour the traveltimes picked over the 3D data block. This event is probably linked to a channel or a system of channels, with a general NNW-SSE direction.
The horizontal event indicated by the red arrow in the right-hand side section of Figure 3 around 320 ms is also a channel feature: it corresponds to a channel flank that has been displaced in horizontal position when the block was tilted.

Events at 300 milliseconds: gas/oil contact

Some W-E crossline sections display horizontal events making an angle with the dipping event characterizing the top of the Sergi Formation and stopping abruptly in its western part (Fig. 5, right). These horizontal segments stretch for about 800 m and lean against the reflection at the top of the Sergi Formation. In the N-S inline direction (Fig. 5, left), the horizontal segment seen around 300 ms is shorter. It extends over a distance on the order of 150 m, which is approximately the length of a gas/oil contact in a 13 m thick layer dipping at an angle of 5° (13/sin 5° = 149 m).

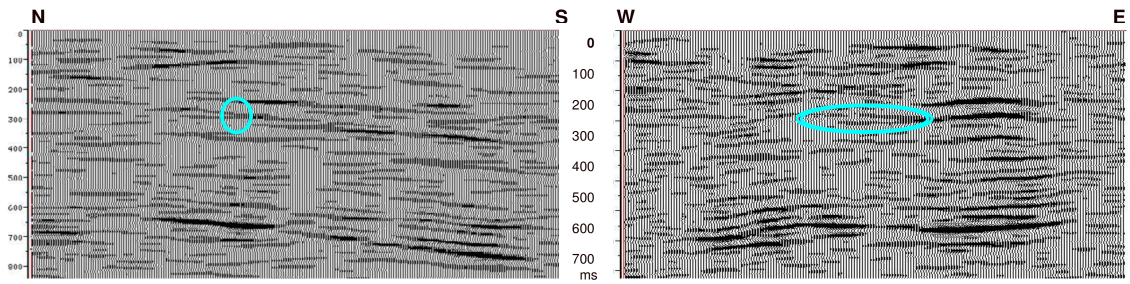

Figure 5. North-South inline section (left) and West-East crossline section (right) showing the seismic signature of the gas/oil contact (horizontal reflections within the light blue ellipses).

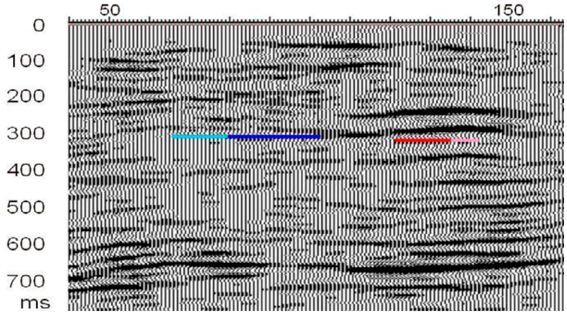

Figure 6. Picked gas/oil contacts displayed on the West-East crossline section of Figure 5.

The dark blue segment displayed in Figure 6 was picked at 300 ms by considering the zero crossing between a negative arch and a positive arch. The event can be followed further west at the lower limit of the negative arch (light blue line). To the east, the horizontal segment picked abuts onto the lower part of Sergi's top. East of this low point, another horizontal event can be picked at 308 ms at zero crossing (red line) and possibly extended eastward at the lower limit of the negative arch (pink line). The difference of 8 ms observed between the two horizontal events corresponds to a depth difference of 12 m assuming a P-wave velocity of 3000 m/s. This picking thus reveals the presence of two gas caps on both sides of the NNW-SSE faults with no communication with each other. Well logs acquired in new boreholes drilled in 2004 found the gas/oil contact at 348.5 and 351 m below sea level west of the faults, and at 366 m, i.e. 15 m lower, east of the faults.

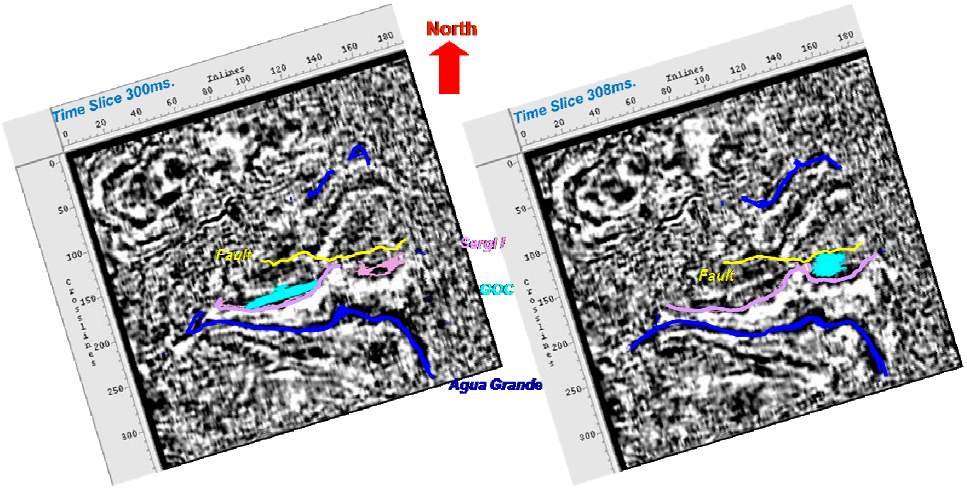

Figure 7. Time slices at 300 ms (left) and 308 ms (right). Picked gas/oil contacts in light blue.

In the western part, the picked horizontal surface at 300 ms occupies a strip roughly parallel to the northern fault, but separated from it (Fig. 7, left). Its width in the inline N-S direction is roughly 150 meters. In the eastern part, the picked surface extends northward up to the northern fault (Fig. 7, right). There, oil and gas are in contact with the northern fault. Close to the fault, the reservoir dip decreases and the gas/oil contact has a larger extent southward. The vertical projection of the picked horizontal surfaces onto the structural map of the top of the Sergi Formation (Fig. 8) encounters this surface at depths of about 362 m below sea level in the western part and 366 m in the eastern part.

CO_2 accumulation at acquisition time

No gas was present at the discovery of the oil reservoir. However, due to the fall in pressure accompanying the oil production, some gaseous hydrocarbon may have appeared in the reservoir. We assume that most of the gas present in the subsurface is CO_2.
The sketch presented below show that the CO_2 accumulation is separated in two parts by a structural low and by North-South faults (Fig. 8, red dashed lines). The area comprised between the main W-E fault (Fig. 8, red solid line), the North-South faults and the 362 m contour line is estimated at about 0.73 km^2. In the western part, the surface picked as gas-oil contact is a rectangle of 1000x150 m^2 (Fig. 8, striped blue zone). There is no evidence of this gas/oil contact further west but it is likely that this contact extends up to the western side of the main W-E fault. The same assumption holds eastward up to the central N-S faults. The surface of the gas/oil contact in the western compartment (Fig. 8, whole blue zone) is estimated at 0.27 km^2.

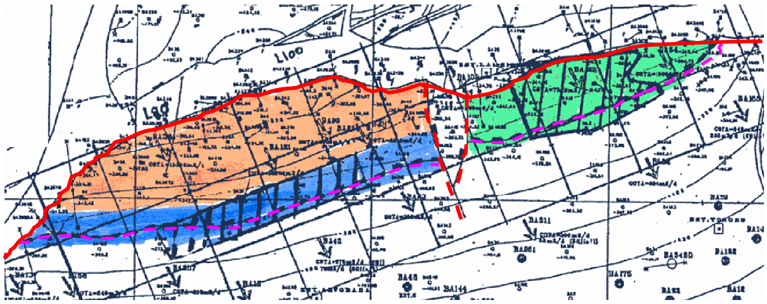

Figure 8: Projection of the horizontal surfaces interpreted as the gas/oil contact onto the structural map of the top of the Sergi formation. The 360 m contour level is represented by a magenta dashed line.

The gas-filled rock volume above the gas/oil contact is equal to half the product of the reservoir thickness (13 m) by the surface of the gas/oil contact, i.e., about 1.76 10^6 m^3. The volume of the zone entirely filled with gas (depicted in orange in Fig. 8) is therefore $(0.73-0.27)\times 13\cdot 10^6 = 5.98\cdot 10^6\,\mathrm{m}^3$. Similarly, the area between the northern fault and the 366 m contour line in the eastern compartment (Fig. 8, whole green zone) is estimated at 0.24 km^2. The gas-filled rock volume is again half the product of the thickness by the surface, i.e., about 1.56 10^6 m^3. Therefore, the gas-filled rock volume is estimated at $(1.76 + 5.98 + 1.56)\ 10^6 = 9.3\ 10^6\ \mathrm{m}^3$.

With an average porosity of 22 % and an initial water saturation of about 24 %, assuming that CO_2 replaces oil but not water, we infer that the volume occupied by the gas is about one sixth (0.22 × 0.76) of the volume of the rocks where CO_2 is present. The total gas volume is then about $9.3\ 10^6 / 6 = 1.55\ 10^6\ m^3$.

Following the injection of carbon dioxide, the pressure in the reservoir went up to 1.5 MPa, at which it stabilized in 1995 (Lino, 2004). At that pressure and at the reservoir temperature, CO_2 has a density of about 50 kg/m^3 (Xu, 2006). The total mass of stored CO_2 is therefore estimated at some $1.55\ 10^6 \times 50 = 77\ 500$ metric tons. Obviously, the error affecting this estimate could be huge and this figure should only be taken as a rough evaluation of the mass of stored CO_2. At the time of the 3D seismic acquisition, about 280 000 tons of CO_2 had been injected (Lino, 2004). Only a part of it was stored in the reservoir.

Conclusions

The presence of the CO_2 injected in the 13 m thick reservoir of the Buracica field only manifests itself by a slight indentation of the seismic waveforms. We have shown that the gas/oil contact can be revealed by directional filtering of the seismic data to enhance the horizontal reflections.

Two gas caps separated by a fault and with no communication between them were detected and mapped. This mapping allowed us to evaluate the depth of the gas/oil contact and to estimate the volume and mass of the stored carbon dioxide within the reservoir.

Acknowledgments

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