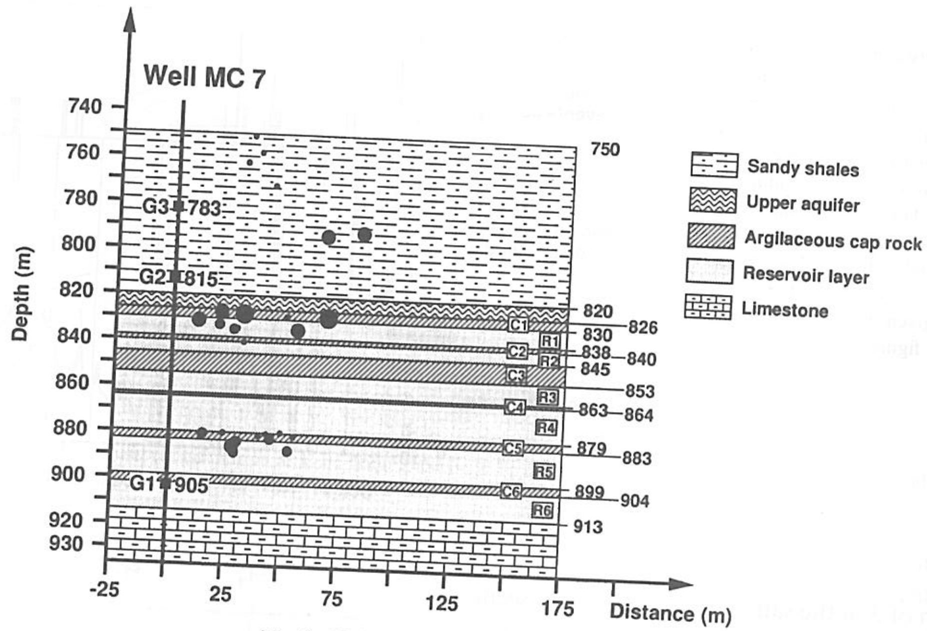


Fig. 9. 2D-location of microseismic events.

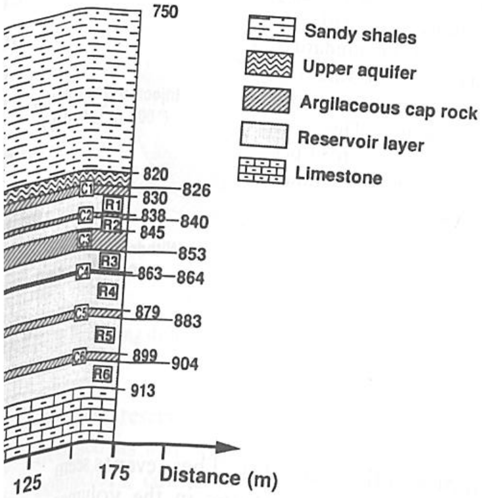
This interpretation is in agreement with the fact that argillaceous cap-rocks C2 and C4 do not act as sealing layers as C1 and C5 do.

Thus events in group 1 give the boundaries of the active part of the reservoir structure: the set of layers where gas can be stored.

Events in group 2 are located above the reservoir in sandy shale layers. In these areas pore pressure variations are supposed to be very small as only very weak pressure variations have been observed in the upper aquifer. A maximum of 0.1 MPa has been recorded in some places for a pore pressure variation of 2.4 MPa in the reservoir. But generally the mean pressure increase in the aquifer is about 0.04 MPa for pressure variations of 1.5 to 2.5 MPa in the reservoir. Pressure variations in the upper aquifer are also time delayed from those in the reservoir. The small amplitude of pressure variations in the upper aquifer is due to:

- the great extent of this sandstone layer compared to the reservoir layers used for gas storage;
- the petrophysical properties (20% porosity and 1D permeability);
- the fact th[...]

directly resulting from gas injections and withdrawals. For group 1 events stress variations generate microseismicity at the boundaries of the layers where the pore pressure changes. In the case of group 2 events, as there is no pressure continuity between fluids in the aquifer and the upper layers and fluids in the reservoir layers, triggering of microseismic activity results more from mechanical effects than from hydraulic ones. Variations of effective stresses in these layers depend more on variations of *in-situ* stresses than on pore pressure. Pore pressure variations outside the reservoir layers may result from matrix compressibility effects. A more accurate interpretation would require pore pressure measurements in the vicinity of well MC7. Unfortunately the pressure was not recorded in this well but only in some other wells located far from well MC7, making interpretation difficult. Nevertheless it is interesting to note that the four events recorded at the end of April 1992 appeared just after a pressure decrease of 0.8 MPa at well No. 18 due to withdrawal. Taking into account the distance between this well and well MC7, the threshold of pressure variation required to generate acoustic activity was probably quite small



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Active monitoring—walkaway VSP measurements

Walkaway VSP measurements were made to monitor the displacement of the gas bubble around well MC7. The seismic line centred on the well straddles the gas bubble limit where it was in February 1991 (Fig. 1) and runs along a road along which the surface source was deployed. The maximum offsets were 870 m to the west and 966 m to the east. Forty-six vibrator sections were recorded with the three permanent sensors. The seismic raypaths are outlined in Fig. 10. There is a 45° slant for the furthest ones. The ray-paths are vertical for source locations in the vicinity of the well.

Using 3-component records enabled us to determine the slant of the direct wave raypaths at each geophone; this gives a more accurate view of the tomographically imaged zones at reservoir levels (Fig. 11). The vertical raypaths cross the reservoir in the vicinity of the well; oblique raypaths cross the different reservoirs further away: 100 m for R3 and 150 m for R1.

To scrutinize the first arrivals we found it convenient to have them lined up (Fig. 12). The first period of the direct wave remains very homogeneous from one offset to another and from one geophone to another.

The first arrival was picked with an accuracy of one hundredth of a ms by using a parabolic interpolation; the sampling rate was 1 ms.

The walkaway VSP was recorded three times: in July 1991, in October 1991 and in April 1992 (Fig. 2). Between the different recordings, travel times for the same offset varied slightly, by about one millisecond.

The main variations are due to a change in the LVL in relation to changes in weather conditions or to a variation in the vibrator coupling from one experiment to another.

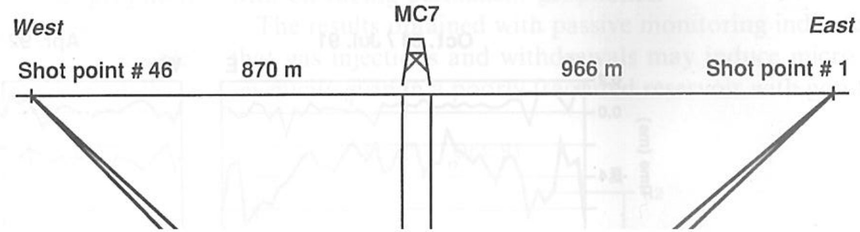
Variations of transit time② from one experiment to another are shown in Fig. 13 as a function of the source offset, i.e. as a function of the obliqueness of the path. Variations of this transit time from one offset to another are some hundredths of a ms, and the curves reveal steady variations along the line.

Between October and July 1991 there was a variation of the transit time between depths of 783 and 815 m (Fig. 13A—curve α), i.e. above the reservoir where gas was injected. For vertical paths this variation is a decrease of about 0.3 ms. This decrease in transit time increases as a function of obliquity and is more or less proportional to the length of the raypath inside the layer considered. The decrease of the transit time corresponding to an increase of the velocity of about 3–4% may result from a compression of the layers above the reservoir resulting from gas injection as was previously suggested in the section concerning passive monitoring.

Transit times above the reservoir show no change between October 1991 and April 1992 (Fig. 13B—curve α'). There is no clear explanation of the difference between curves α (variation of the transit time) and α' (no variation of the transit time), both related to geophones above the reservoir.

Concerning the variations of the transit time in the reservoir between depths 905 and 815 m and between July and October 1991 (corresponding to an injection of 170.10^6 Sm^3 of gas③) there is a small increase (0.1 ms) for wave slant paths to the west of the well (Fig. 13A—curve β). This increase is smaller as the paths get closer to the well and disappears for the eastern part of the line. Between October 1991 and April 1992 (corresponding to a withdrawal of 350.10^6 Sm^3 of gas) transit times inside the reservoir decreased from 0.3 ms in the

Fig. 10. Diagram of the raypaths of direct waves in the walkaway VSP. The plotted raypaths are related to the farthest positions of the vibrator. The shaded rectangle depicts the reservoir.



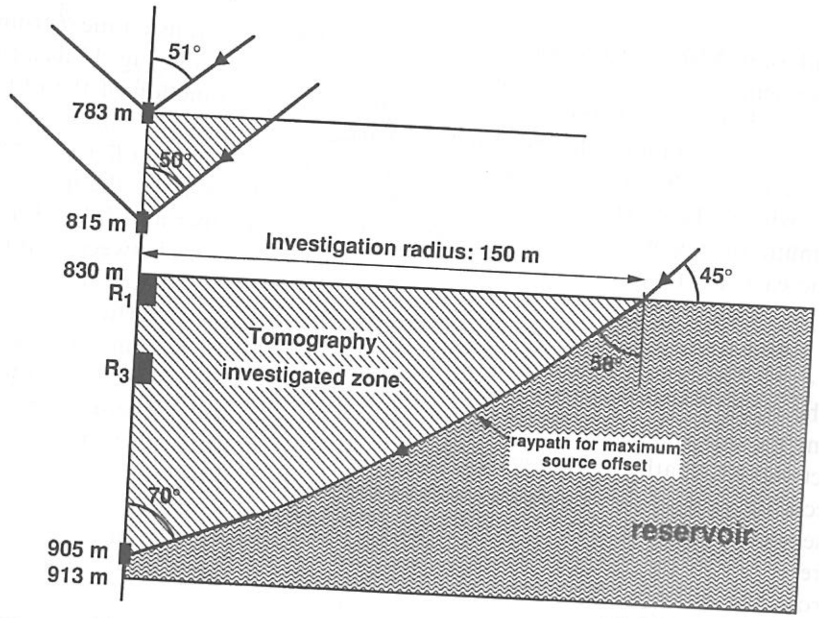


Fig. 11. Diagram of the zone tomographically imaged between the horizontal planes containing the permanent geophones. Lateral range reaches 150 m at the level of reservoir R1 and 100 m at the level of R3. Angles have been calculated by using the three components.

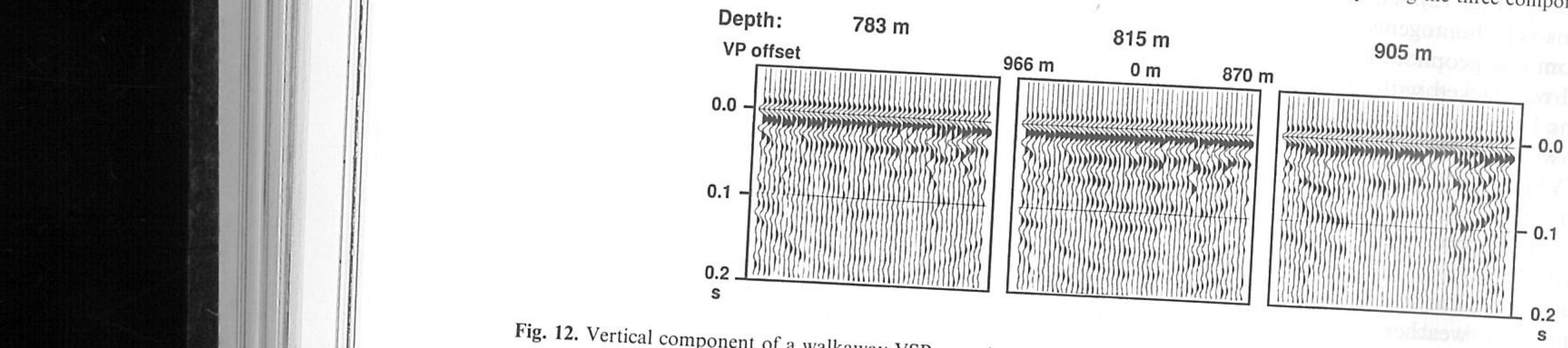
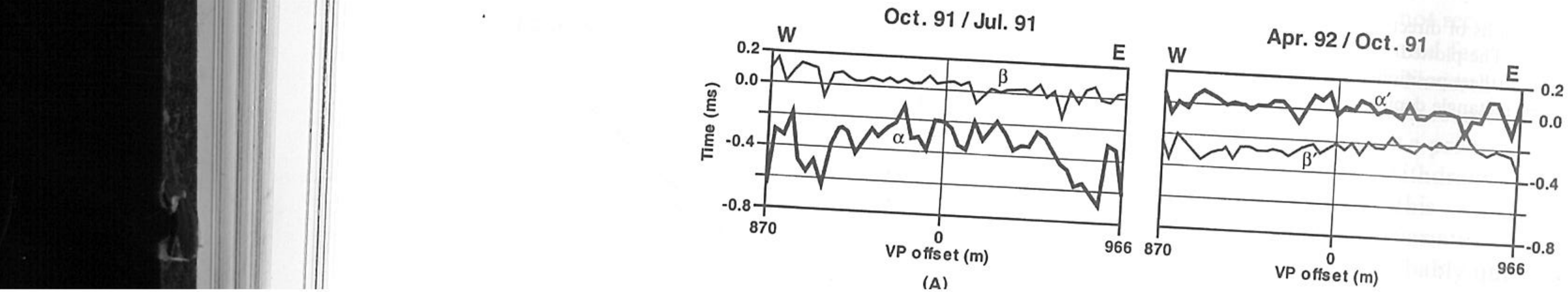
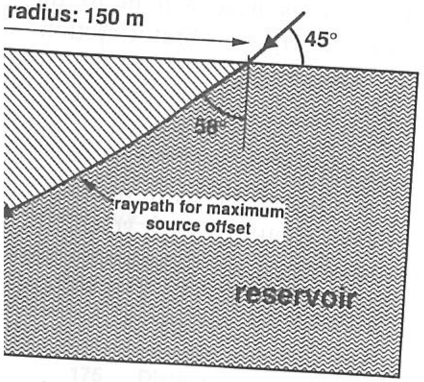
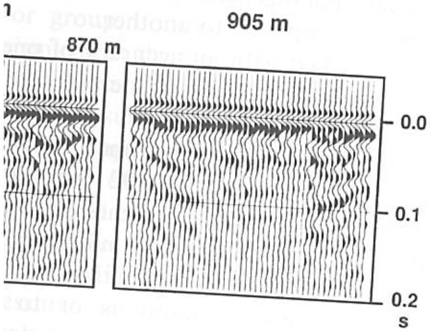


Fig. 12. Vertical component of a walkaway VSP record (July 1991) after lining up and normalization of the first arrival. On the X-axis: source offset. On the left the record obtained with the geophone at 783 m, in the middle with the geophone at 815 m, on the right with the geophone at 905 m depth.

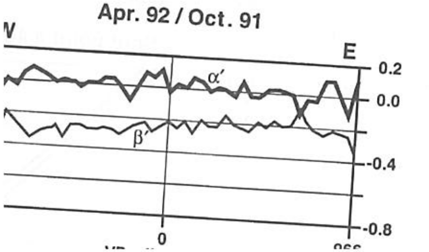




ntal planes containing the permanent geophones. Lateral range reaches
have been calculated by using the three components.



ing up and normalization of the first arrival. On the X-axis: source
ddle with the geophone at 815 m, on the right with the geophone at



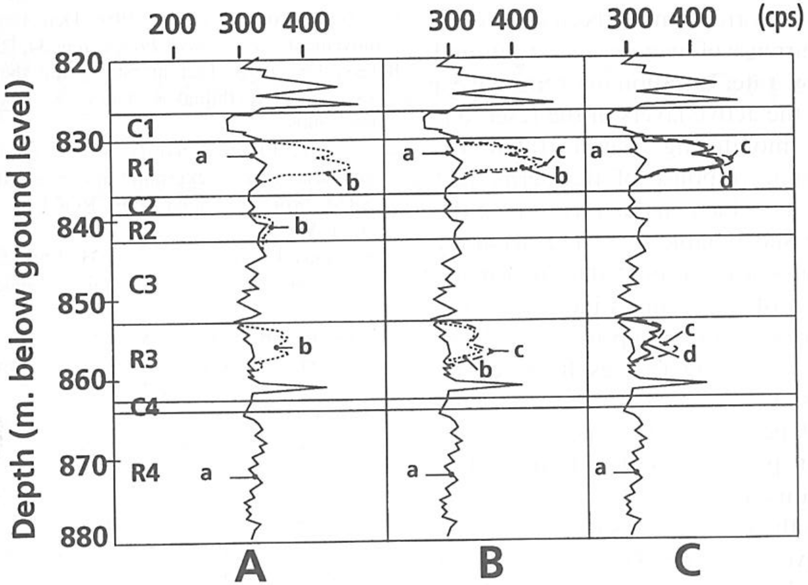


Fig. 14. Neutron log recorded in well MC7 (in cps) in the reservoir. Curve a (solid line) shows the neutron log recorded before the first gas injection and is used as a base curve in A, B and C. (A) Curve b (dotted line): neutron log recorded on 4 July 1991. It shows an increase of cps due to gas saturation. There is gas in levels R1 and R3 and some gas shows in R2. (B) Curve c (dashed line): neutron log recorded on 7 October 1991. There is a slight increase of gas saturation in R1 and a larger one in R3, in relation to curve b, after a gas injection phase. (C) Curve d (bold solid line): neutron log recorded on 7 April 1992. It shows a small decrease of gas saturation in R1 and a larger one in R3, in relation to curve c, after the withdrawal phase.

The amplitude ratio④ shows random variations from one offset to another. Nevertheless the same variation can be found for the three geophones; this enabled us to assume that the surface conditions or the ground coupling of the vibrator were entirely responsible for these variations.

The ratios (October 1991/June 1991 and April 1992/October 1991) of the amplitude ratios give a value very close to one (Fig. 15) with a dispersion of some percentage points.

This result emphasizes the good quality of the measurements and the preservation of the geophone sensitivity after being downhole for two years.

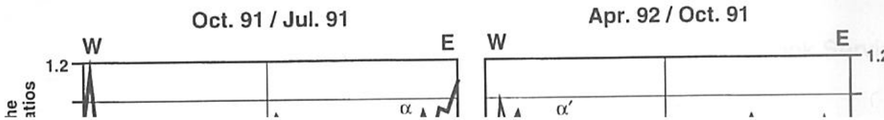
In Fig. 12 a reflection (upgoing wave) is clearly visible. This reflection has been picked on the records at all three

Picking has been performed for different offsets in the surveys of October 1991 and July 1991. Unfortunately, due to the high noise level, the accuracy is about 0.5 ms, which is completely insufficient to confirm or invalidate the measurements made for direct arrivals.

Conclusions

As far as we know the field experiment carried out at Germigny-sous-Coulombs is the first to achieve acoustic monitoring of an underground gas storage reservoir with on-tubing permanent geophones.

The results obtained with passive monitoring indicate that gas injections and withdrawals may induce microseismicity even in a poorly fractured reservoir with good



petrophysical properties. A correlation has been established between the time of occurrence of microseismic events and variations of the gas flow rate. Location of events gave a good determination of the active layers in the reservoir.

The active seismic monitoring demonstrated the consistency of the seismic response of the permanent geophones over two years, which enabled us to pick the first arrivals in a clear and reliable way. The accuracy given by the permanent sensors (about 0.05 ms) made possible the observation of the changes induced in the reservoir by the displacement of gas up to 150 m from the instrumented well, extending the results given by neutron logs in the observation wells.

In the future, use of permanent sensors at different depths would make it possible to detect any effect resulting from variations in the stresses applied to reservoir layers and to the cap rock, using a combination of active and passive surveying. Risks of leakage in gas storage reservoirs and compaction in oilfields could be forecast. During hydraulic fracturing it would be possible to map the fracture and, in naturally fractured reservoirs, knowledge of the location of mechanically active fractures would contribute to better management of production.

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