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Accuracy Analysis of Micro-Earthquake Hypocenters in a CO_2 Sequestration Experiment

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Summary

The accuracy of hypocenter location is critical for monitoring CO_2 sequestration. If they are located below the cap rock depth, they allow safe control of the expanding plume. However, if they affect the cap rock and the overlaying formations, the injection should be stopped immediately. The hypocenter depth is often poorly controlled, when using sparse seismological stations at the Earth's surface (as in global seismology), mainly because the 3D velocity model used is not so detailed or reliable. At a reservoir scale, however, active seismic surveys can provide such a model with good accuracy, thereby increasing the precision of hypocenters' estimate.

Keywords: *micro-earthquake, hypocenter, CO_2 sequestration, cap rock, seismic*

Introduction

In global-scale seismology, the uncertainty in the hypocenter coordinates of major earthquakes is in the order of a few kilometers. A higher precision is not relevant for planetary studies and for civil protection. When dealing with micro-earthquakes at a reservoir scale, instead, the accuracy of hypocenters' locations is very important, especially since their pattern may highlight non-sealing faults and preferential fluid pathways, which are critical for reservoir monitoring and production optimization. At both scales, however, we cannot quantify the accuracy of our estimates experimentally, as we can do for the depth of formation tops, as predicted by seismic surveys and validated by well logs. In this paper, we present an indirect validation for a real experiment carried out in the In-Salah field (Algeria), where the induced micro-seismicity is due to CO_2 sequestration. This analysis allows us to clarify the reliability of micro-seismic data in this specific experiment, and also to provide clues for further improvements. We have modeled the synthetic traveltimes for hypocentral locations based on the ongoing CO_2 injection, and compared the estimates with the known coordinates and time origin. Beside the real recording geometry, composed both of surface and well receivers, we analyzed possible alternatives, trying to minimize further the relocation errors.

A detailed description of the algorithm used for estimating the hypocentral coordinates is presented by Vesnaver et al. (2010). The key principle is minimizing the misfit between recorded and modeled traveltimes for P and S wave arrivals. In addition to the (x_H, y_H, z_H) hypocenter coordinates, a time origin t_0 is estimated too, using possibly the Wadati's method. This approach requires a few coupled P and S arrivals to be picked at the same receiver, which is not always possible. When applicable, however, it reduces significantly the cross-talk between errors in the time origin t_0 and the hypocenter depth z_H. When only P arrivals are available, an estimate is still possible, but the uncertainties increase by an order of magnitude.

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The In-Salah experience

Figure 1 shows a 3D view of a simplified model of the In-Salah field, where an experiment of CO_2 injection is ongoing. For its detailed description, the reader may refer Ringrose et al. (2009). We notice that the reservoir is a very thin layer, indicated by the green arrows in the figure, at a depth of about 1800 m. The CO_2 is injected in an aquifer below the gas field. The white dots indicate the simulated hypocenters, distributed around the injecting wells. The blue dots show the positions of the receivers, part of which are placed in a few boreholes, at higher and intermediate depths, and part at the surface close to the well heads. This recording geometry is not ideal but cheap, requiring minimal efforts for the receiver maintenance and security.

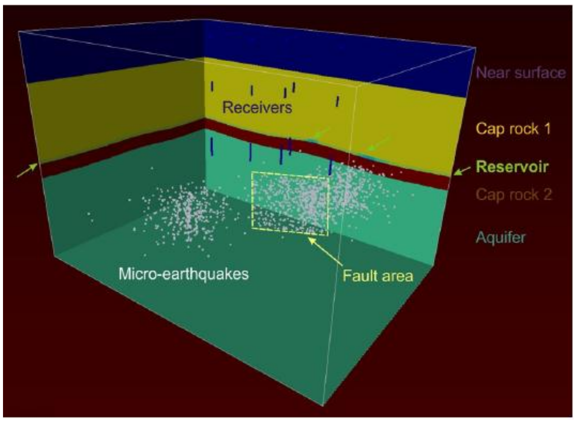

Figure 1: 3D view of the synthetic model that mimics the In-Salah test site.

Figure 2 shows the ray paths joining all available receivers with the simulated micro-earthquakes. Only part of the reservoir (blue colour) is covered and hence, we cannot expect any contribution from passive seismic outside such an area. Figure 3 is a 3D view of the reservoir layer.

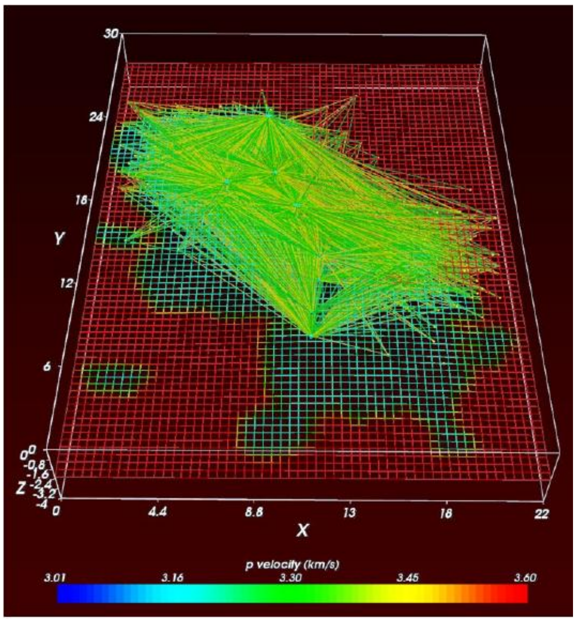

Figure 2: The available ray paths for seismic tomography cover only part of the gas reservoir.

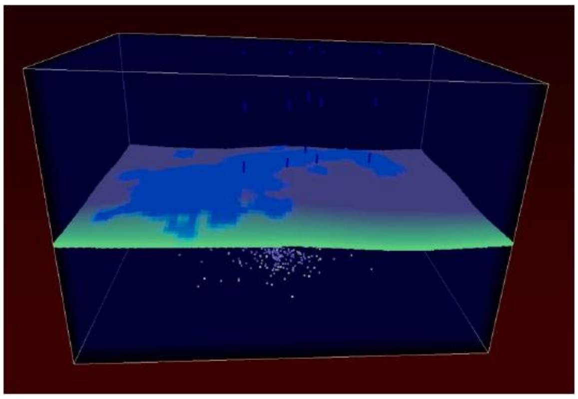

Figure 3: 3D view of the layer with the gas reservoir only. The white dots show some of the micro-earthquakes hypocenters.

As the reservoir layer is only 30-40m thick, reflection tomography can reconstruct only its top and the bottom of the underlying cap rock layer, for a total cumulative thickness of about 200m. However, the resulting averaged velocity is totally unable to detect the modest contribution of the reservoir (Figure 4).

A good result is obtained exploiting different information sources. While keeping the contribution of reflection tomography to define the upper reservoir interface and the initial velocity model (i.e., Figure 4), we used the available wells to interpolate the reservoir thickness, and the micro-earthquakes as additional illumination points. Figure 5 shows that, in this way, we can delineate the gas field overlying the injection area with a good accuracy (see Figure 3), in the area covered by raypaths.

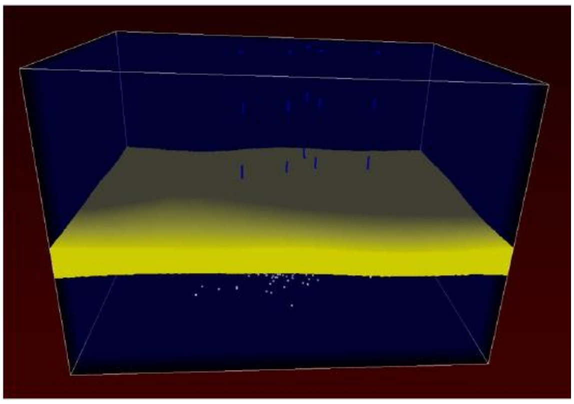

Figure 4: Estimated velocity in the reservoir vicinity by 3D Reflection tomography.

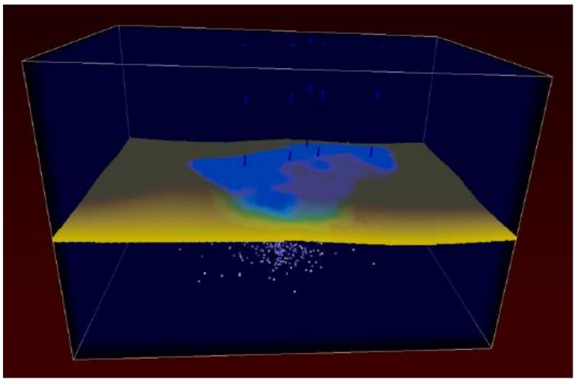

Figure 5: Velocity at the reservoir using reflection tomography for the reservoir top, well data for its thickness, and passive seismic for tuning the velocity estimate.

Conclusions

The joint processing of passive and active seismic data provides significant improvements to the imaging of CO2 pathways, cap rock integrity and, in the specific case of the In-Salah experiment, it allows improving the delineation of the overlying gas field.

References

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