A Straightforward Workflow for Monitoring CO_2 Storage

Estimating and appreciating the distribution of injected CO_2 allows better understanding of the reservoir and identifies potential gas migration. Using PaleoScan™ provides a fast method from seismic conditioning to carbon capture storage quantification.

MARC-ANTOINE DUPONT, SVEN PHILIT and FABIEN CUBIZOLLE, Eliis

contact@eliis.fr
www.eliis-geo.com

In the context of climate change and the search for atmospheric CO_2 reduction, CO_2 sequestration has been underway for a couple of decades and a few carbon capture storage projects have been implemented and monitored.

An abundance of data and a good understanding of the Sleipner CO_2 storage project offers the opportunity to test workflows aimed at quickly accessing the CO_2 volumes injected into the reservoir. Two comparative methods for estimating and understanding the distribution of injected CO_2 are proposed. The first method is a semi-automatic approach where geobodies are delineated from an attribute threshold value identified as highlighting the CO_2 accumulation anomaly, as mapped on a series of geologically consistent surfaces. The second method takes advantage of the AVO tool newly implemented in PaleoScan™ to generate geobodies derived from an Intercept vs Gradient correlation and the identification of gas anomaly classes. The two methods are finally compared in the light of the available literature.

Sleipner

The Sleipner field is located in the North Sea, about 250 km offshore Stavanger, Norway and was initially developed in 1974 as a gas field, with production from Palaeocene and Jurassic sandstone formations. The younger Utsira Formation, intersected by the Sleipner Block, was later envisioned as a storage reservoir and 12.1 Mt of CO_2 was injected between 1996 and 2010. The injected gas is monitored using 4D seismic (Figure 1).

The Miocene Utsira Formation consists of a regional sand aquifer capped by a thick, sealing shale formation (Figure 1a). The gas accumulation is distributed into several sand units which are separated by thin clay/mudstone layers of limited extent that vertically compartmentalise the reservoir. The injection well has been drilled to reach the base of the Utsira sand formation at about 1,100m below sea level.

The Geobody Extraction Workflows

Method 1: The Horizon Stack delineation

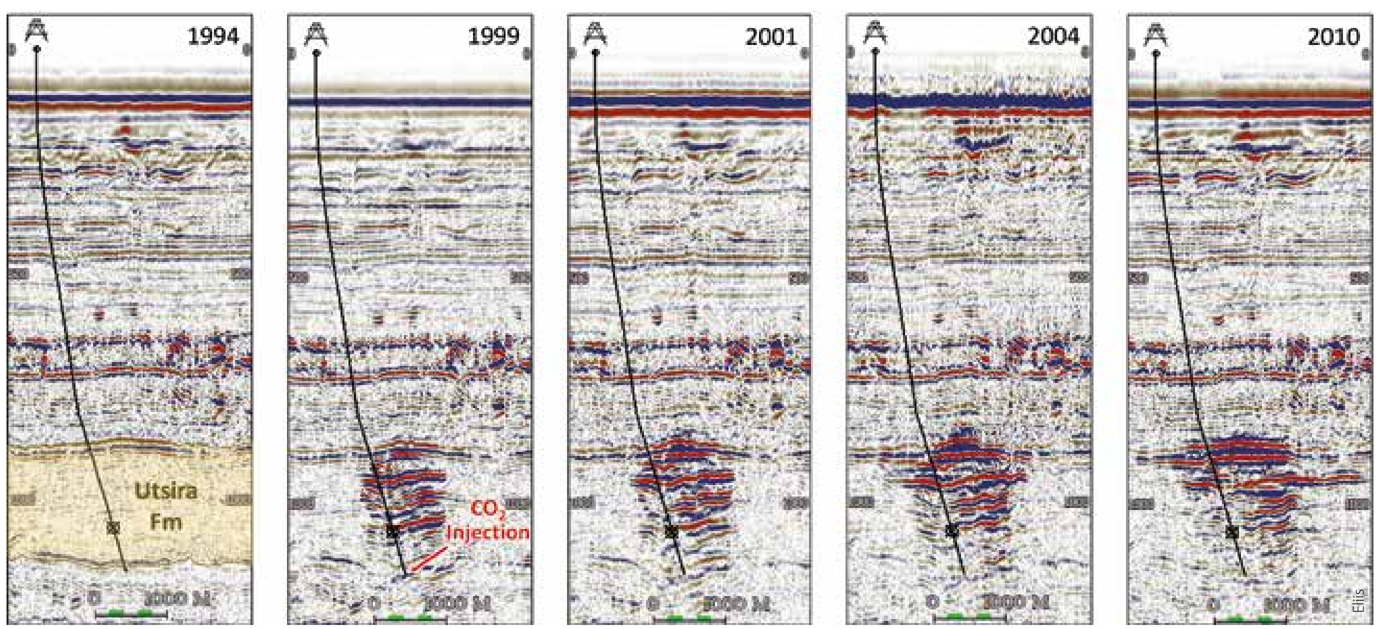
The first method relies on the traditional workflow for geobody extraction in PaleoScan™. This workflow involves a semi-automated seismic interpretation to constrain the creation of a Relative Geological Time model. This model is then used to generate a dense series of surfaces or "horizon stack" on which attributes are mapped to highlight anomalies and allow the geobody extraction.

Because the efficiency of the automated seismic interpretation depends on the quality of the seismic data, two conditioning processes are subsequently applied to the seismic data before interpretation commences (Figure 2). First, a structure-oriented smoothing is applied to reduce the noise effect (Figure 2b). The structure-oriented smoothing relies on a Gaussian smoothing technique based on the dip variation of reflectors to enhance the reflector continuity. Secondly, as reflectors in some stratigraphic intervals of low-impedance contrast (e.g., carbonates, shales) are characterised by low amplitudes, a spectral balancing is applied to the signal to boost the reflectors of lower amplitudes (Figure 2c). These coupled conditioning steps offer an optimised seismic interpretation.

The seismic interpretation is then performed via a semi-automated method: the horizons are auto-tracked across the entire seismic volume, chrono-stratigraphically sorted, and then used as geometrical constraints to generate a geological time model. The geoscientist can manually refine the interpretation of every horizon and iteratively increase the accuracy of the model. Thanks to the previous conditioning, the auto-tracked horizons are now more continuous (auto tracking enhancement of approximately 20% in the Utsira reservoir) and of better quality, thus shortening the manual interpretation time. The models are generated from the interpretation of the 1994 vintage seismic (prior to gas injection) and 2010 vintage (after 12.1 Mt of CO_2 had been injected).

From the model, a stack of a hundred horizons is extracted from both vintages of the seismic. The average energy attribute, chosen because this efficiently highlights the amplitude anomaly induced by gas accumulations, is computed from the original seismic vintages and then mapped on each horizon of the stack. The gas accumulation signal is extracted semi-automatically based on the mapping: a range of average energy amplitudes is used to delineate patches on every horizon intersecting the anomaly (Figure 3a&b). This

Figure 1: Seismic section near the injection point where the impact of the CO_2 accumulation is observed in the Utsira Formation from 1994 to 2010 (vertical scale in ms) [Inline1853].



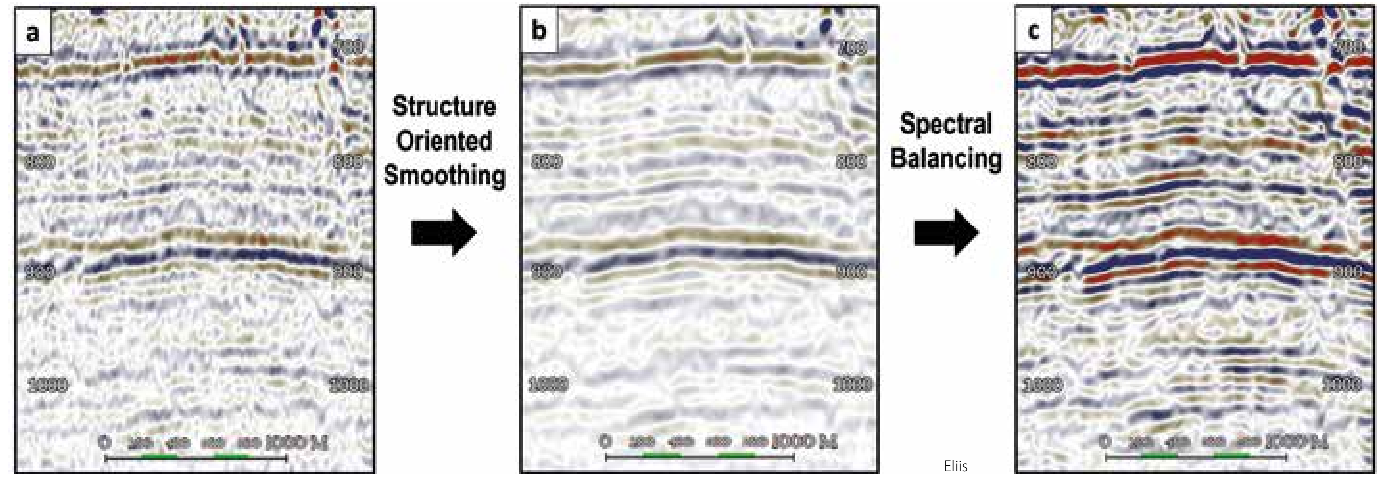
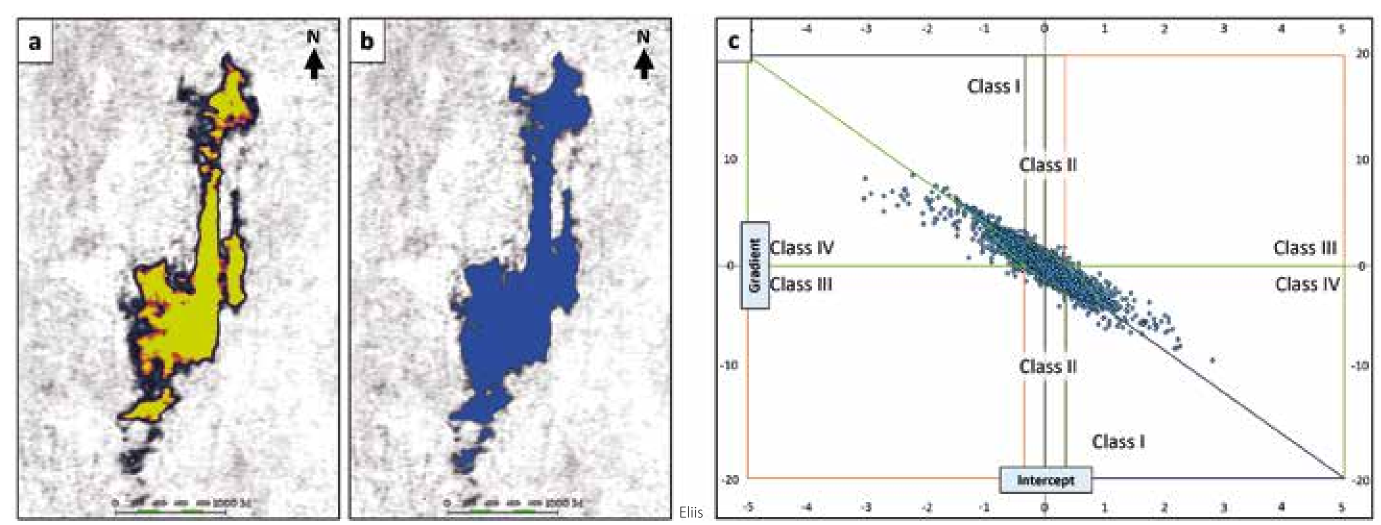


Figure 2: Vintage seismic from 1994 with different conditionings. a) Original seismic. b) Structure oriented smoothed. c) Structure oriented and smoothed, then spectral balanced. Same colour bar and colour setting for a), b) and c). PaleoScan™.

Figure 3: Horizon stack with average energy mapping highlighting the gas accumulation: a) gas accumulation evidenced high amplitudes and b) thresholded high amplitude range (blue) used for the anomaly delineation and geobody extraction. c) Intercept vs gradient cross plot with the different classes. PaleoScan™.



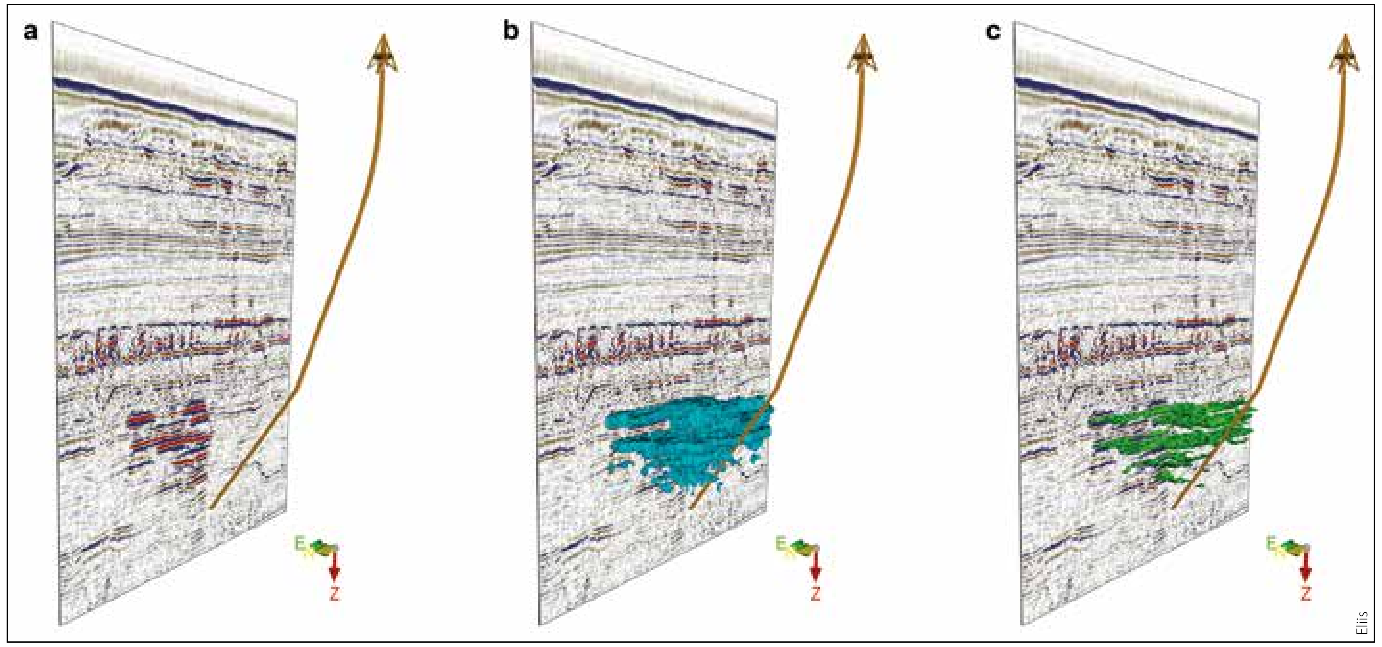


Figure 4: a) Injected well and seismic inline 1843, with b) the geobody obtained via Horizon Stack delineation, and c) the geobody obtained via AVO post-stack analysis. PaleoScan™.

series of delineations defines a volume ultimately extracted as a geobody (Figure 4b). The volumetrics of this geobody is converted in the vertical depth domain using a conversion factor of 1.8m per ms for an output of ca. 0.467 km^3. To permit a coherent comparison with the observations reported by the literature, we account for an average reservoir porosity of 36%, an average water/CO_2 saturation of 0.8, an average CO_2 density of 675 kg/m^3 and a dissolved fraction of 0.1, in accordance with the values commonly reported. With these considerations, we estimate a CO_2 accumulation of 82 Mt of injected CO_2 in 2010 vs 12.1 Mt in reality. This large overestimation is underlined by the bulky shape of the geobody, where the several gas layers are not clearly differentiated.

Method 2: The AVO post-stack analysis

With Amplitude Variation with Offset (AVO) post-stack volumes with near, mid, and far angles approaching or lower than 30 degrees, the intercept and gradient volumes derived from the Shuey two-term approximation can be correlated to perform an AVO analysis and obtain the CO_2 anomaly geobodies. These attributes, highlighting fluids or petrophysics properties, are cross plotted to perform an AVO reservoir classification (Figure 3c). By delineating the background trend and identifying the AVO anomalies in the cross plot, one can interpret that this corresponds mainly to a class IV anomaly. This class is supposed to represent the main gas-bearing reservoirs (different sand layers bearing the CO_2). The corresponding extracted geobody contains nine distinct layers as suggested in the literature (Figure 4c). Following the same assumptions as the previous method, the volumetrics of these layers is of ca. 0.095 km^3, estimated to a CO_2 accumulation of 20 Mt. This value is quite close to the measured one (12.1 Mt). The compartmentalisation of the gas accumulation is properly captured by the structure of the geobody.

Take-Home Method

Despite the use of volumetric approximations for simplification (e.g., time/depth conversion factor, porosity, CO_2 density), we see in the context of gas monitoring, that one method yields more precise output than the other. The traditional Horizon Stack delineation method could be attractive because it allows visualising of the anomaly mapped on geological consistent surfaces. However, in addition to involving a longer workflow, the choice of the mapped attribute and the selection of the anomaly amplitude range, significantly impacts the volumetrics of the extracted geobody, in this case leading to a CO_2 accumulation overestimation of more than 600%. On the other hand, while the AVO post-stack analysis is independent from conditioning, seismic interpretation and Horizon Stack creation from a model, it also yields a volume estimation of injected CO_2 close to that depicted in the literature. In this work, the overestimation of 165% is most likely induced by imprecisions in the Intercept vs Gradient cross-plot class delineation and an inaccurate time/depth conversion factor. Besides the more accurate volumetrics, the vertical CO_2 compartmentalisation reported by the literature is neatly reproduced through this workflow. On balance, the Horizon Stack delineation method may be appropriate for the identification of more subtle features belonging to a given geological surface such as channels. It seems that the AVO analysis remains an efficient tool for quick gas accumulation assessment and particularly for future CO_2 gas storage monitoring.

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