Introduction

To “substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2 degrees Celsius while pursuing efforts to limit the increase even further to 1.5 degrees” as stated in the Paris Agreement (UN, 2015), most greenhouse gas control scenario include massive CO_2 geological storage also called CCS. According to the IEA, from over 40 Mtpa CO_2 in 2021, CCS yearly capacity needs to increase to 1.6 Gtpa CO_2 in 2030 (IEA, 2021). To make it happen, subsurface industry will have to overcome (amongst other) the following two critical challenges: **social acceptance** and **Monitoring, Measurement and Verification** (MMV) as technically and economically viable for long term monitoring (50-100 years) (Lumley, 2021).
In this abstract, pros & cons of frequent full field 4D seismic monitoring strategy are presented, and a supplement/alternative approach is introduced (Morgan et al., 2020) that capitalize on the key features of CCS to calibrate flow models where and when needed with an agile focused seismic measurement.

4D seismic, proven technology for CCS conformance & containment with limitations for long term monitoring

The world’s oldest CO_2 storage project Sleipner located offshore Norway has demonstrated that 4D seismic images were **technically** the most appropriate technology for CO_2 storage monitoring (Furre et al., 2017). Over the 20+ years of this CCS project, ten 3D seismic campaigns have been acquired to monitor the CO_2 plume behavior, thus reducing uncertainties (Wierzchowska et al., 2021).

Although technically successful, there are three main limitations attached to 4D frequent full-field images for CCS monitoring: costs, operations, and social acceptance.

- **Cost**: with a seismic image every two years on Sleipner, seismic images were able to fine tune the reservoir understanding (Wierzchowska et al., 2021), but they did not highlight major “surprises” in the CO_2 plume behavior compared to predictions & measurements (Furre et al., 2017), jeopardizing part of the value of **frequent** full-scale 4D seismic images. Several CCS players are considering **frequent** 4D seismic images as a solution economically “too heavy” to represent a viable monitoring tool (Lumley. 2021).
- **Operation:** on a 50-100 years timelapse, new infrastructures will be built making full field 4D images impractical. Figure 1 (left) is showing an example of the highly obstructed Qarn Alam field in Oman where the exploration 3D seismic can’t be replicated 20 years after due to new infrastructure and/or exclusion zones, discarding full field 4D seismic as a monitoring option.
- **Social acceptance**: a full field 4D seismic image, impose to re-acquire dense source/receiver locations on large area. This mobilizes a lot of equipment and crews (onshore/offshore) increasing a safety exposure, an environmental footprint (Figure 1) and CO_2 emissions generating in urban & agricultural areas local resistance for frequent seismic acquisitions.

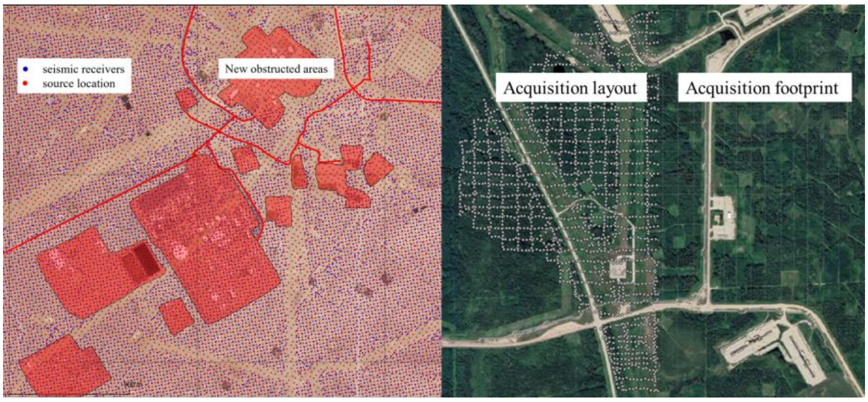

Figure 1 *Left panel: Qarn Alam 3D 2005 seismic layout, showing in red new surface obstructions. Right panel: satellite view of a Canadian O&G field, overlayed with the 4D seismic layout. The layout has been cut in the middle to highlight the visible acquisition footprint on the satellite image.*

Finally, some areas are known to be seasonally impractical for full field seismic operations preventing seismic monitoring even if needed. As an example, the seismic Canadian season is winter while it is summer for the North Sea, preventing 4D seismic acquisitions for more than half a year in both cases.

CCS key features enabling flow model-based monitoring

MMV are part of several regulations (US EPA, EU CCS Directive 2009/31/EC) with strong focus on conformance, containment & contingency (Furre et al., 2017). For the two first criteria, operators need to convince regulator that they **understand the behavior of the CO_2 plume anytime & anywhere**. To do so in an economically and environmentally sustainable way, we propose to capitalize on the following two CCS specific features:

- **Simple reservoir model**: as geological methane gas storage, CCS sites are targeting simple geology to offer maximum safety.
- **Strong sensitivity to seismic measurements**: CO_2 injection is generating a strong 4D seismic response enabling very frequent reliable seismic detections (monthly) (Lumley. 2021) (Furre et al., 2017) (Wierzchowska et al., 2021) (Li et al., 2013). To illustrate how quickly a 4D seismic signal could be generated by a CO_2 injection, we present in Figure 2 a Petro Elastic Modeling (PEM) done on a depleted oil field turned into a CCS project.

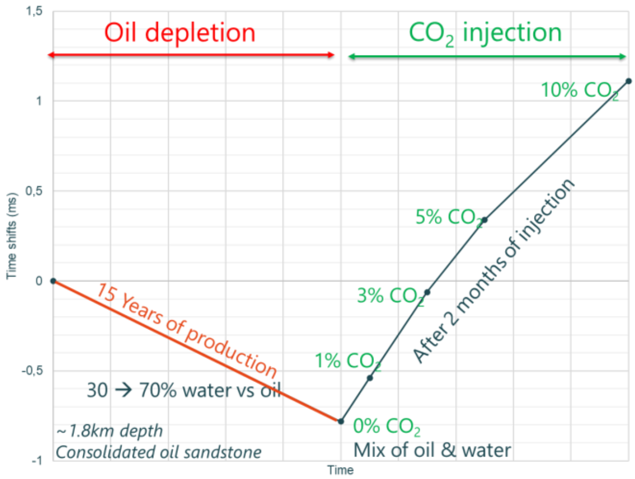

Figure 2 *Simulation of the 4D acoustic seismic response in terms of time shift values. The red curve shows a -0,8ms time shift (monitor -base) generated by +15 years of production. The green curve is showing a 2ms time shift with just a 10% CO_2 saturation increase achieved in two months.*

Strategy: certify flow models & predictions with focused detection to rely on them

Dynamic flow model is a key tool for CCS conformance & containment prediction. Operators are investing & developing them to better accommodate CO_2 fluid behavior. Considering the strong sensitivity of seismic measurements to CO_2, it is doable to frequently verify & calibrate flow models to avoid any major surprises. Simple reservoir model should limit the number of calibration points to be monitored simultaneously.
These points (that are called Spots) will vary during the CCS life of field and required an agile non-invasive solution. Observation wells are not optimal for this purpose as they create integrity weaknesses and are not agile.

We call this approach focused monitoring.

Figure 3 illustrates how the monitoring of the Sleipner field could have looked like with a spot measurement approach (Al Khatib et al., 2021). Spot detection could have been compared with flow predictions.

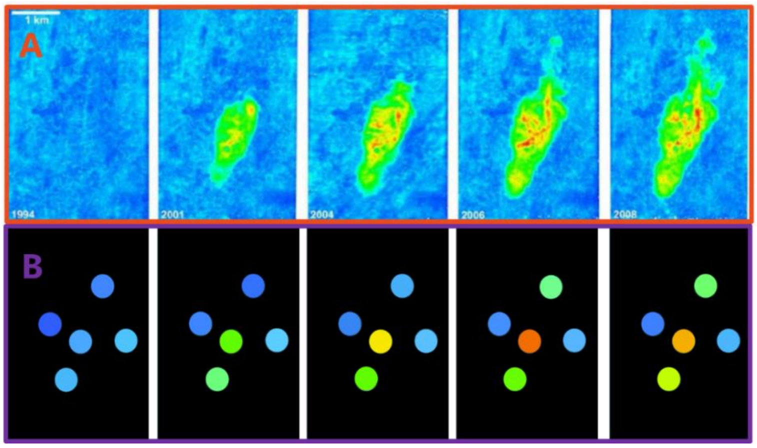

Figure 3 *Modeling of spots monitoring concept (Al Khatib et al., 2021). A: Time-lapse seismic images showing CO_2 detailed plume evolution. B: Modeling of a focused detection on critical spots of interest. Average 4D value had been taken to model the Spot 4D response.*

If spot measurements are validating the same changes than models were able to predict, then models can be trusted. If not, a full field 4D seismic (for example) could be undertaken to correct models and predictions. By combining frequent and focused measurement with flow model predictions, CCS operators can demonstrate to the regulators that they understand the behavior of CO_2.

Big data analysis to build a frugal focused seismic monitoring solution

The focused frequent monitoring approach capitalizes on expensive and dense existing assets: exploration seismic, structural modeling & flow predictions. The optimal source and receiver location per spot is identified to detect a 4D signal (Morgan et al., 2020). The focused monitoring layout compared to full-field layout is illustrated on the Figure 4 with a real case example on CO_2 injection (Brun et al., 2022, unpubl. results).

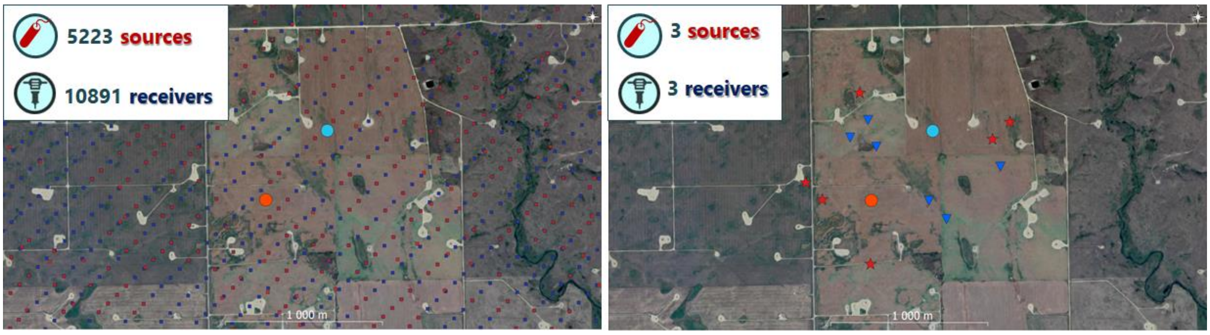

Figure 4 *EOR CCS example of focused monitoring layout. Left, full field layout. Right, focused layout*

Equipment reduction in the field is massive (%1000), enabling a cost-efficient acquisition with more safety, less footprint and negligeable CO_2 emissions compared to conventional solutions. The solution can be operated in highly obstructed areas, adapted to future obstructions, be mobilized quickly wherever & whenever needed providing an agile solution. Frequent acquisitions (and even permanent) are economically and operationally possible to support flow model validation. Figure 5 is showing a detection result on two Spots in a CCS EOR example (Brun et al., 2022, unpubl. results) using a non-permanent setup and legacy data as baseline (14 years old). These results could be considered as qualitative “virtual observation well” with capabilities to detect CO_2 arrival in and above the reservoir (for caprock integrity) in a kind of “on-off” CO_2 detection.

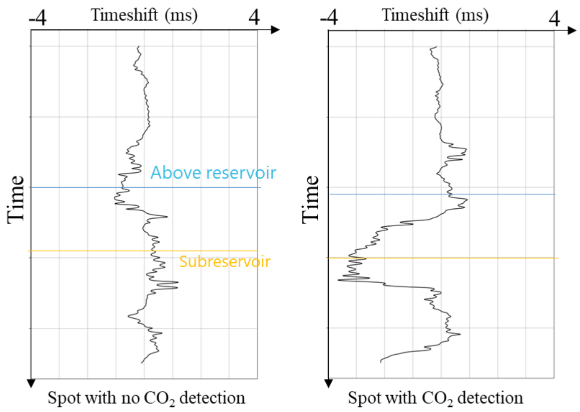

Figure 5 *Sliding time shifts for each of the antenna. 2 horizons above and below the reservoir are indicated as an information for the detection (Brun et al., 2022, unpubl. results).*

Conclusion

In this abstract we proposed to use accurate flow models as a long-term monitoring tool. Models will be validated by focused seismic measurements whenever & wherever needed, to demonstrate the capability of the model to accurately understand CO_2 plume behavior. Injection phase will require frequent monitoring on various location to cover CO_2 conformance. Long term containment MMV could be achieved with focused measurements by looking at identified weaknesses in the subsurface: structural leaks, fault networks, etc. Limitations to this detection compared to 4D images are a lack of spatiality, resolution & quantification of changes, aspects that could be offset relying on flow model predictions, or/and other measurement tools like 4D seismic, or well measurements.

To push further the cost and environment effectiveness of the solution additional synergies with flow models & passive measurements could be investigated. As an example, microseismic network and/or Distributed Acoustic Sensors could be integrated in the Spot design as potential receiver; resident Remotely Operated Vehicle might be used to position nodes offshore.

This approach was selected as the seismic monitoring solution of Project Greensand and the consortium will invest ~1,3M€ on spots monitoring with an ambitious R&D plan.

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