Managing large volume time-lapse datasets for sustainable carbon storage in subsurface reservoirs

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Abstract

High sampling density data sets are delivering time-lapse monitoring information for sustainable carbon storage projects in subsurface reservoirs, and require application of industry accepted optimum practices for large volume data management. The use of surface and subsurface geophysics data spans the project lifecycle of carbon storage, from evaluation through measurement, time-lapse monitoring, reporting, and verification. Industry technology providers provide cloud-based platforms to store and deliver fiber optic time-lapse geophysical monitoring data acquired during and after CO2 injection. Operators and technology providers are jointly developing models for data types used in sustainable geologic carbon storage, and contributing them to industry standard, open-source data platforms. Increased visibility for large volume time-lapse monitoring datasets drives innovation for ingestion, enrichment, and consumption of reservoir geophysical data over the decadal lifespans of sustainable carbon storage projects. This paper provides insight into the types and volumes of data that are associated with sustainable carbon storage.

Introduction

Geophysical data contributes to reservoir evaluation and time-lapse monitoring of storage sites for CO2. Many of these data types, such as seismic surveys, vertical seismic profiles (VSP's), sonic logs, and gravity and magnetics surveys, have long histories of effective usage in reservoir analysis and benefit from established systems of record and mature data workflows (Lumley, 2019). To support streaming delivery of validated and indexed large volume seismic data to cloud or on-premises users evaluating time-lapse monitoring, Brazilian operators have announced agreements to use technology contributed to the Open Subsurface Data Universe (OSDU™ Data Platform) for presenting data to interpretation applications as virtual files (Maxwell, 2023). Geophysics reservoir data serves as input to model reservoir fluid dynamics in numerical simulation studies of depleted shale gas reservoirs under CO2 injection for geologic storage (Weber et al, 2019). As carbon storage projects move from front-end engineering design toward financial investment decisions, the need for additional geophysical data will increase for both collecting information on baseline conditions before injection, and longer-term measurement, monitoring and verification (MMV) of reservoirs. Government regulators at local, state, and federal levels may mandate much of the geophysical reservoir data collected under operating license and environmental approval requirements. Geophysical data required to demonstrate reduction of risk of seal leakage can vary depending on regulatory regime and the geologic repository selected. Required geophysical monitoring periods for operators, for example, can vary from 10 to 20 years (Rocha and Costa, 2021), or be linked to the closure of utilization and storage activities (Draps and Jumanti, 2023). .

Methods

Data management practitioners are interested in developing validated and indexed systems of record for reservoir geophysics data that supports sustainable carbon storage projects. The systems will adopt and adapt industry accepted optimum practices for providing data that is Findable, Accessible, Interoperable, and Reusable (FAIR) and meets government regulatory requirements that attempt to balance the need for open and democratized public data against legitimate intellectual property and privacy concerns (OECD, 2019). The systems will need to accommodate exponential increases in data volumes and rates of delivery for time lapse monitoring (Heaivilin and Weider, 2018), and the delivery of new data types (Figure 1) as technical innovation continues (Fawad and Mondol, 2022). These increases in multiple facets of Big Data will require use of technologies such as edge computing (He and Paulsson, 2021) and intelligently tiered cloud storage with public cloud service providers. As sensors deployed at injection sites decrease in size and increase in data capabilities, resource operators will also need to consider the carbon footprint of sustainable time-lapse monitoring data (Karagiannis and Filipovic, 2022).

At the evaluation and screening stages, reservoir geophysics data collected during exploration and production of mature fields establishes a base line understanding of fluid and gas pathways in the reservoir (Dino, 2009). Fully instrumented appraisal, injection or monitoring wells deliver real time and time-lapse geophysical monitoring with Distributed Acoustic Sensing (DAS) deployments for 3D baseline images indicating geologic integrity (Wilson et al, 2021).

After injection has begun, indirect surface geophysical techniques including electrical resistivity tomography (ERT) and magnetotellurics (MT) are used instead of traditional methods of downhole pressure and chemical monitoring to overcome limited geospatial coverage and increased cost of multiple monitoring wells (Yang et al, 2019). When considering older legacy wells for remediation and future use in CO2 injection programs

(Figure 1), Controlled-Source Electromagnetic Modeling (CSEM) can indicate corrosion levels in well casing at depth (Romdhane et al, 2022).

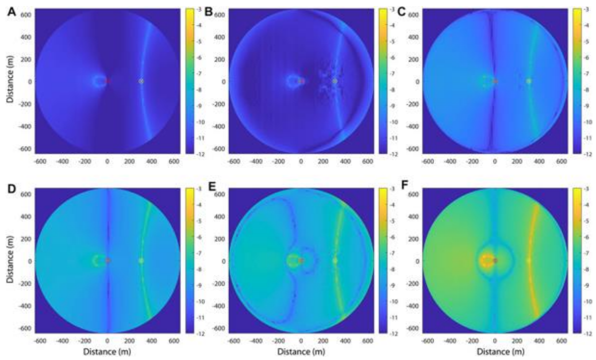

Figure 1 *– CSEM modeling data from a well with differing levels of casing corrosion. The plots show the absolute value of the derivative of the horizontal component of the modeled electrical field across a cross section of the well at the seafloor, with decreasing conductivity due to corrosion at depth (From Rompdhane et al, 2021).*

Examples

To prepare data systems to accommodate the large volumes of reservoir geophysics data generated by sustainable carbon storage projects, the working group on geologic storage of the OSDU™ Data Platform Forum is defining standard metadata attributes and reference lists. With active participation from four of the five largest global supermajor oil companies by reserves, they are focusing on three domains of data acquisition; subsurface, near-surface, and remote sensing (Figure 2).

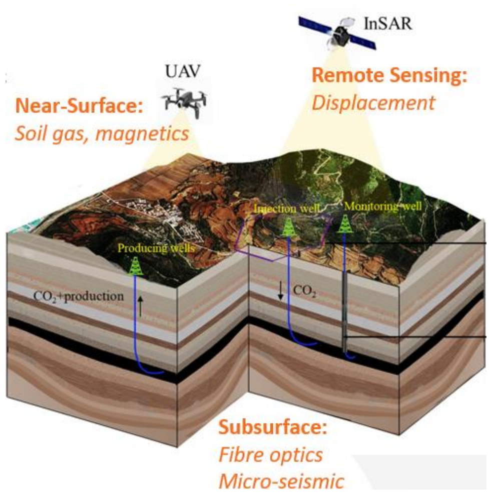

Figure 2 *– Schematic diagram of acquisition systems for geophysical data being defined for geologic storage projects by the OSDU™ Forum working group. (After Zhang et al, 2022).*

In the remote sensing domain, satellite borne Interferometric Synthetic Aperture Radar (InSAR) data detects surface deformation monitoring over geologic storage sites (Zhang et al, 2022) to identify the underground migration direction of CO2 plumes. InSAR data augmented by slope data collected from Autonomous Aerial Vehicles (AUV's) can compensate for effects of steep terrain on radar imaging. Because the InSAR technology provides large-scale, continuous time-lapse monitoring on decadal time scales, the volume of data can overwhelm current systems.

At the near surface, multiple gas concentrations measured from subsurface soil horizons over years of baseline and time-lapse monitoring will generate large datasets, augmented by process-based analytics from smart sensors collecting calibration data on temperature, humidity and pressure factors that can effect readings from gas chromatography (Romanak and Bomse, 2020). Sensors will collect hundreds of thousands of geophysical readings per site using advanced techniques for automated data collection. This data will need to be stored, managed and delivered and derivative analytic products will add to data volumes and time-lapse monitoring at industrial scale deployments.

The subsurface domain has the largest potential to increase volumes of geophysical reservoir data collected for sustainable carbon storage, while utilizing existing data standards more than other newer data types. The OSDU™ Forum working group addresses industry standard data formats for delivering real-time and processed micro-seismic data (OSDU, 2021). This data assists in time lapse monitoring of a reservoir's response to CO2 injection by indicating induced fracture event characteristics, location and magnitude (Verndon et al, 2015). Interpreted results of real time micro-seismic data in interpretation and analysis software use industry standard exchange formats (Figure 3) such as wellsite information transfer standard markup language (WITSML) specifications (Energistics, 2017).

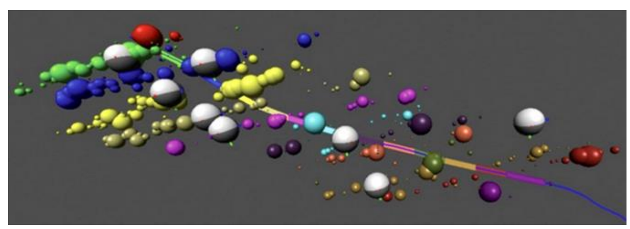

Figure 3 *– 3D view of microseismic event trends with source mechanisms at selected hypocenter locations along a wellbore. The plot covers approx. 1km of drill depth (From Williams-Stroud et al, 2012)*

This standard encapsulates work developing open data exchange standards and oil and gas information sharing protocols. Affiliation with The Open Group (Gnyp, 2022) enables broader access to existing industry-adopted data transfer standards by the data management community. Synergy in the standards community continues to support data management for sustainable carbon storage as part of the larger global energy transition with more efficient collaboration and stronger standards evolution. The trend in recognizing overlap and transferring governance continues with global energy data professionals groups also collaborating with the OSDU™ Forum to ensure that robustly defined data expectations from sustainable carbon storage programs support data trust, reliability and consistency on the cloud-based platform (PPDM, 2023). Industry working groups review, refine, and supply data definitions, reference lists, schemas, and facet definitions for data quality, and terms and definitions can appear by reference in open source schema, in some cases filling recognized gaps with full schemas in OSDU™ formats.

Robust data reference lists and vocabularies provide reusability of geophysical reservoir and time-lapse monitoring data in validated systems of record for sustainable carbon storage. Within the OSDU™ Forum, a Reference Values Committee is reviewing and improving reference lists in coordination with schema definition teams. Established published workflows ensure that Forum members can consume reference lists quickly and efficiently to support new data types as they emerge. Now delivering 35 new lists for the OSDU™ Platform, data organizations have jointly provided up to 235 reference lists across a wide footprint of subsurface data. The lists are available to practitioners in the data management community under open-source agreements, allowing subject matter experts to make them easy to consume in the OSDU™ schema definitions. Curated reference lists are critical to achieving the interoperability goal of FAIR data. As the OSDU™ Forum starts work on new subject areas supporting sustainable carbon storage, members of working teams have access to documentation and other materials developed by standards workgroups, including the existing industry standard PPDM relational Data Model. Many elements of the data model now reside in OSDU™ Forum Domain Data Management Services (DDMS).

Fiber optic sensor data for subsurface reservoir time-lapse monitoring will transform workflows for digital data management. A single fiber optic cable in an injection or monitoring well at a carbon storage site is capable of recording and delivering data on temperature, stress, and acoustics (Sun et al, 2021). Some fiber optic data benefits from existing industry standard data formats supported in cloud-based open-source and cognitive compute data platforms. Distributed Temperature Sensing (DTS) data, for example, uses the temperature dependency of backscattered light from a fiber optic cable to produce a plot of temperature vs. depth along a borehole. Early applications and versions of data compression only stored only data that changed by a given threshold from a previous value and remote databases only stored data from targeted zones in the well. Partially processed and interpreted data from a remote server using periodic store-and-forward systems led to uncertainties in data quality, security and ownership. Using industry standard data exchange formats (Cramer et al, 2008) well engineers can reduce the amount of vector data transmitted from well sites.

With the long periods required for time-lapse monitoring of carbon storage sites, fiber optic technology can generate up to petabytes of digital data in storage and management workflows (Figure 4). Edge processing techniques will ensure this data remains findable, accessible, interoperable and reusable. While DAS deployment can reduce cost when compared with repeated collection, processing and interpretation of conventional surface 3D seismic surveys (Warner et at, 2020), this must be balanced against the cost and effort of managing and delivering the large volumes of time-lapse monitoring data (Yavuz et al, 2019).

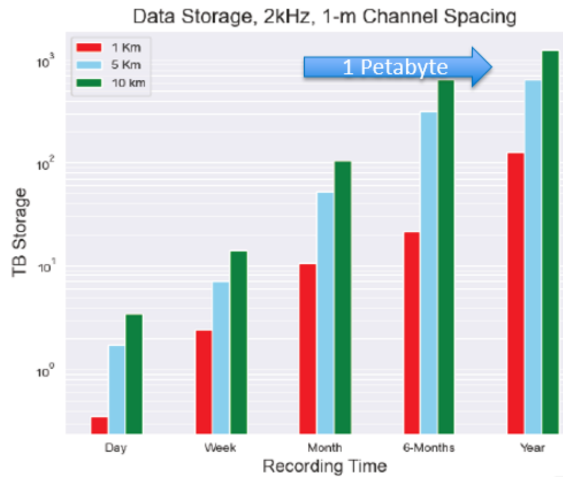

Figure 4 *– Volume of data generated by various cable lengths of fiber optic sensors installed vertically and horizontally from a single well for continuous time-lapse monitoring periods up to one year.*

As the availability of data bandwidth and storage increases with the adoption of cloud-first data strategies, it becomes more important to support efficiency in data transfers between service providers and operating companies of complex data types supporting reservoir time-lapse monitoring of sustainable carbon storage. Sharing of standardized DAS and DTS data sets occurs with Production Markup Language (PRODML) version 2.0, developed and improved by a group in the open consortium of over 42 member specialists in upstream oil and gas data management (Energistics, 2018).

This standard provides a significant improvement in data management, removing numerous requests from operators to service providers for adoption of proprietary file formats for DAS and DTS data. Such requests had a negative impact on service quality due to increased costs from time and support for data delivery. The single data format enables timely delivery of data from the wellsite, making the data more accessible and interoperable. Efforts from the consortium group also support the development of a PRODML 2.1 DAS data-streaming standard (Naldrett, 2018).

With DTS data collected independently and continuously during operations, operators can measure and monitor temperature profiles within the wellbores in real time. When these results are available for interoperation with reservoir time-lapse monitoring and operations data including downhole pressures, temperatures and injection rates, the migration patterns of CO2 plumes in the subsurface are characterized and verified. Details on the presence of CO2 within target injection zones and time of arrival of CO2 plumes at monitoring wells can be stored and managed with other operational data for the project, and used to optimize injection into specific formations, or as combined product streams (Mawalkar et al, 2020).

The PRODML data transfer specification also provides a standardized way to describe the path of the fiber optic cables on a site installation, as a top-level distributed data object, containing the collection of optical components such as terminators, connectors, splices and turnarounds (Figure 5) and the connection network. This allows data managers to collect and preserve important metadata about the installation and reuse it for data analysis or applications such as well decommissioning (Energistics, 2016). The model provides an audit trail of any changes to the network that could have an impact on quality, sensitivity, or confidence of reservoir geophysics or time-lapse monitoring data during sustainable carbon storage.

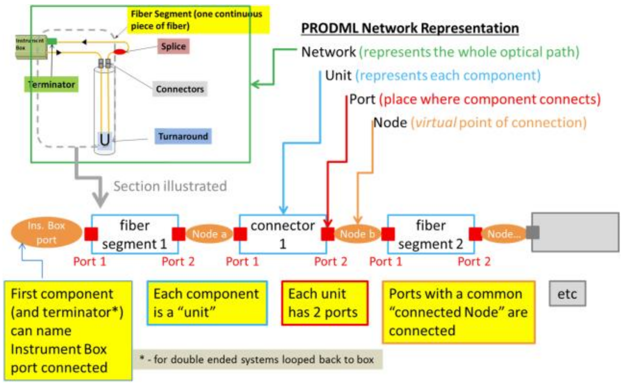

Figure 5 *– A data modeling view of the optical path components in a PRODML Product Flow Network Model (from Energistics, 2016).*

Backscattering is also sensitive to hydromechanical deformation induced by CO2 injection reservoir pressure, and Distributed Optical Fiber Strain Sensing (DFOSS) generates real-time permanent and time-lapse monitoring of CO2 leakage, wellbore and cap-rock integrity. Fiber optic cable installed horizontally at the surface in shallow trenches creates a 3D model showing uplift from injection and subsidence from production in the reservoir (Amer et al, 2023). Analyzed data from permanently installed, real-time, low-cost and data-efficient time-lapse monitoring systems creates more and larger derivative data products on emerging cloud-based data platforms.

The WITSML and PRODML data transfer protocols enable delivery of DAS, DTS and DFOSS data along a wellbore. The large volumes of data attainable with permanent fiber optic monitoring cable deployments and lower cost surface sources such as Surface Orbital Vibrators (SOV's) that provide continuous active time-lapse seismic monitoring will overwhelm the capabilities of many currently deployed data platforms. Data collection and processing systems for continuous time-lapse monitoring systems can require as much as 960 terabytes of near line capacity in the field and extensive real-time processing and archiving of recorded data to reduce recorded volumes from hundreds of terabytes to 10's of gigabytes per day for transmission (Isaenkov et al, 2021).

Large data cubes (Figure 6) will be managed using open-source flexible storage formats for multi-dimensional (up to 6D) signal data. Data compression levels are selected to balance between precision, performance and storage (OSDU, 2023) Data management practices for processing, delivering and visualizing multiple dimensions of reservoir geophysics and time-lapse monitoring data available in DAS cubes will benefit from techniques in other data intensive industry sectors, such as astrophysics (CORE Innovation, 2023).

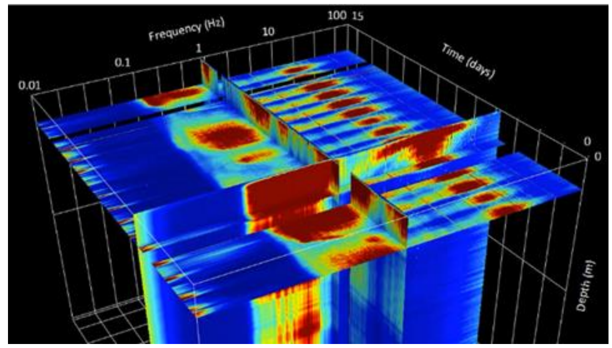

Figure 6 *– A SEGY cube of fiber optic passive DAS data processed to display depth, time and frequency (from Pevzner et al, 2022).*

Conclusions

Resource operators will need to work with large volumes of densely sampled data sets created by reservoir imaging and time-lapse monitoring of sustainable carbon storage projects. Cloud-native standards based on open-source solutions will provide a competitive advantage as detailed data collection supports detection and tracking of injected CO2 down the a granular level of as little as hundreds of tonnes of carbon, or about the footprint of one transatlantic airline flight (Mondanos et al, 2023). Business impacts will be measured using industry accepted optimum practices for reductions in decision data latency (DiMatteo and Agostinelli, 2022). At industrial scales, operators will also be able to demonstrate energy and carbon emission savings from processing data remotely rather than storing large volumes of data at cloud centers (Oliveira et al, 2022). Additional benefits will include demonstrated reduction in data based uncertainty and risk (Wei et al, 2013), and increased return on investment based on application of data driven decisions (Liu et at, 2021).

Many depleted oil fields have large volumes of existing geophysical data from their exploration and development phases used to evaluate reservoir suitability for sustainable carbon storage. As the emphasis from operators turns toward the larger storage capacity of deep saline formations, the need for larger volumes of more recent data will increase (Anderson, 2017), further increasing the need for effective data management strategies and initiatives. Current work by government regulatory agencies on modernizing access to legacy data used in evaluating sustainable carbon storage sites is evidence of this trend (DMIRS, 2021).

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