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Assessing Carbon Storage Potential in the Indus Basin, Pakistan: 4D X-Ray Tomography

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Abstract:

The need for practical carbon capture and storage technologies increases as levels of atmospheric carbon dioxide continue to rise. Geological carbon storage, which is a sequestration of CO2 in subsurface formations, has great potential. This paper explores the potential of the Indus Basin in Pakistan for geological carbon storage and also highlights the role of 4D X-ray tomography as an advanced monitoring and characterization technique. Indus Basin is rich in various sedimentary formations, including the Lower Goru Formation, Sui Main Limestone, and others with reservoir characteristics. International case studies demonstrate the use of 4D X-ray tomography in visualizing and quantifying CO2 behavior in porous media which provides insights into wetting behavior, mineral interactions, and flow dynamics. The objective of this research is to evaluate the feasibility and optimization of the CO2 storage process in specific Indus Basin reservoirs by using 4D X-ray tomography. This further aims to drive the attention towards the addressment of reservoir heterogeneity, long-term CO2 fate, and integrating micro-scale tomography data with larger-scale reservoir simulations to advance carbon storage initiatives in Pakistan.

Keywords: Carbon storage, CO_2 sequestration, Indus Basin, 4D X-ray tomography, geological formations, reservoir characterization, trapping mechanisms, saline aquifers, porosity, permeability, mineralization, cap rock integrity.

1. Introduction

Carbon Dioxide (CO_2) from fossil fuel combustion poses a serious threat to the stability of the Earth's climate (Shah et al., 2024). An urgent reduction of these emissions has prompted an unprecedented research and development of various carbon capture and storage (CCS) technologies. Pakistan is recognized as a nation particularly vulnerable to the unfavorable impacts of climate change and has committed to reducing its carbon emissions under the framework of the Paris Agreement (Ahmed et al., 2024). This commitment marks the critical need for Pakistan to explore and implement effective carbon mitigation strategies. Geological carbon storage, defined as long-term storage of captured CO_2 in subsurface formations, appears to offer a practical approach to this issue. There are many geological reservoirs that may be suitable for CO_2 storage, including depleted oil and gas reservoirs and deep saline aquifers that exhibit sufficient porosity and permeability to host adequate amounts of CO_2, and which also contain overlying impermeable cap rock layers to securely contain the CO_2 (Ahmed et al., 2024). Effectiveness and safety of geological carbon storage projects depend on an understanding of the subsurface environment and monitoring of injected CO_2 over time. For site selection and accurate forecasting of CO_2 behavior, it is important to characterize the reservoir thoroughly. Monitoring after injection is a natural progression towards follow-up

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verification and to recognize any leakage or other possible migration risk (Fentaw et al., 2024). 4D X-ray tomography is another imaging method to permit unique opportunities to enhance our understanding of geological carbon storage operations (Jangda et al., 2024). This imaging method is non-destructive and can image and quantify the flow of fluids in porous media, in addition to rock-fluid interactions, in three dimensional spatial resolution over time (Jangda et al., 2024). 4D X-ray tomography enables time resolved spatial information that allows for recording CO_2 movement and its interactions with reservoir rocks to be visualized at the pore scale and thus allow scientists to directly visualize the base monitoring mechanisms controlling carbon storage (Bultreys et al., 2023).

2. 4D X-Ray Tomography for Geological Carbon Storage

X-ray computed tomography (CT) has established itself as a valuable imaging method. It produces a set of cross-sectional images of an object's internal structure using X-ray data. After taking multiple 2D projections at different angles, it is possible to reconstruct a 3D volumetric image of the sample's distribution of density. The real extension of the methodology to 4D is taking a series of those 3D scans at various points in time. This means we can visualize and quantify the change occurring over time in the sample volume, such as with fluid movement or changing solid matrix (Yashiro et al., 2021; Bultreys et al., 2023).

Utilizing 4D X-Ray Tomography provides several critical benefits to research on geological carbon storage. One of the advantages of 4D X-Ray tomography is its non-destructive nature as it allows repeated images of local sample over time or under different conditions (Bultreys et al., 2024). This non-destructive ability is essential for investigations of the long-term effect of CO_2 on reservoir rocks and for understanding the time-evolution of processes without destroying samples. Also, the high spatial-temporal resolution (i.e., sub-millimeter to few hundreds of microns resolution) of the method allows researchers to observe the movement of CO_2 and the pore-scale trapping mechanisms (Jangda et al., 2024). A pore-scale understanding of how CO_2 can displace formation fluids, become trapped in pore spaces through capillary forces, or attach to mineral surfaces is essential for understanding how to expect it to behave at the reservoir scale.

In addition to visualization, 4D X-ray tomography can be used to quantify the state changes in important reservoir attributes like porosity, permeability, and mineralogy as they evolve over time (i.e. in response to CO_2 injection). The time series of 3D images allow researchers to evaluate and understand the long-term response of the storage formation as the CO_2 progresses, specifically with regard to the dissolution of dead carbonates and/or precipitation of new phases (Noiriel & Renard, 2022). These attributes are central to predicting the storage capacity and injectivity and the long-term integrity of the potential carbon storage site. Lastly, 4D X-ray tomography can show complexity in how CO_2 interacts with the formation brine and rock matrix (Cooper, 2023). These interactions may involve a range of dissolution and precipitation reactions along with changes in the pore network that can be influential in not only the secure trapping of CO_2, but also the potential alteration of reservoir properties at geological timescales.

3. Global Case Studies of 4D X-ray Tomography in Carbon Storage Research

Numerous international research studies have adopted the method of 4D X-ray tomography to study various aspects of carbon geological storage. These experiments employed different types of reservoirs lithologies and experimental conditions, which may provide useful lessons about future carbon storage projects in the Indus Basin.

One area of interest includes understanding the wetting of CO_2 in porous media, predominantly in sandstone reservoirs. Another study used 4D X-ray microtomography to visualize fluid flow and dissolution in limestone with hydrochloric acid. The researchers employed imaging techniques that invoke similar processes of visualizing fluid flow and pore structure to study CO_2-brine-rock behavior in sandstone (Cooper, 2023). By referring to the study's claim to a stop to CO_2 leakage, it highlights the importance of studying CO_2 behavior in the reservoir. Unfortunately, the physical and chemical characteristics of CO_2 and sandstone can be affected by pressure, temperature, and composition of formation fluids, thus altering the storage capacity and security. Consequently, while the author doesn't explain or describe seeing CO_2 wetting behavior in sandstone with a 4D X-ray microtomography, the visualization of fluid displacements and pore structure adjustments is relevant.

Another major use of 4D X-ray microtomography is researching CO_2 storage in carbonate reservoirs and the potential for induced mineralization. Research published in this space has used 4D X-ray microtomography to view the injection of CO_2 into carbonate rock samples, along with the resulting carbonate mineral precipitation (Noiriel & Renard, 2022). Mineral carbonation is a potentially improved mechanism for CO_2 trapping, as it mineralizes CO_2 through stable solid carbonate phases. While mineral trapping is a more effective trapping mechanism, the efficacy depends on the history and specific mineralogy of the carbonate rock and the composition of the formation brine, as seen in the effect of magnesium or calcium ions. Furthermore, changes in water chemistry or brine quality can significantly influence the rates of precipitation and mineral phase, again based on rates of precipitation, mineral type, and formation brine composition. Although research using 4D seismic monitoring has been done in CO_2 injections in carbonate reservoirs, which demonstrates the challenge of imaging thin reservoirs substrates (e.g., thin carbonate formations), the even higher precision of 4D X-ray microtomography can provide areal and time-lapse observations complemented with pore-scales and better visualized observations.

In addition, 4D X-ray velocimetry has been used to directly visualize the motion of CO_2 in a porous rock sample during several injection conditions. 4D X-ray velocimetry measures the velocity and direction of CO_2 flow at the pore scale, which can be used to ultimately validate and improve reservoir models through observations of pore-scale behavior of CO_2. The studies show how reservoir heterogeneity (e.g., fractures and variability in grain size) has a significant impact on CO_2 flow pathways and have implications for trapping efficiency (Bultreys et al., 2024). Some heterogeneities can create preferential flow pathways and others can act as barriers that distribute and store CO_2 after injection. The pore-scale measurements of flow and trapping are also complementary to larger-scale monitoring, such as cross-well seismic and electrical resistivity tomography, that have been applied to tracking CO_2 plume migration and saturations in field projects including sandstone reservoirs. Understanding the pore-scale behavior of CO_2 from 4D X-ray studies of core samples should be an important foundation to base the subsequent interpretation of geophysical datasets collected at larger scales.

4. Potential Carbon Storage Reservoirs in the Indus Basin, Pakistan

The Indus Basin is a large sedimentary basin that covers a large region of eastern Pakistan, has a complex geological history, and has considerable hydrocarbon potential. The geological aspects of the Indus Basin can be divided into the Upper, Central and Southern Indus Basins, which each have different tectonically and stratigraphically organized sequences (Malkani & Malik, 2017). The geological context of the region is important for understanding potential formations in the Indus Basin for geological carbon storage.

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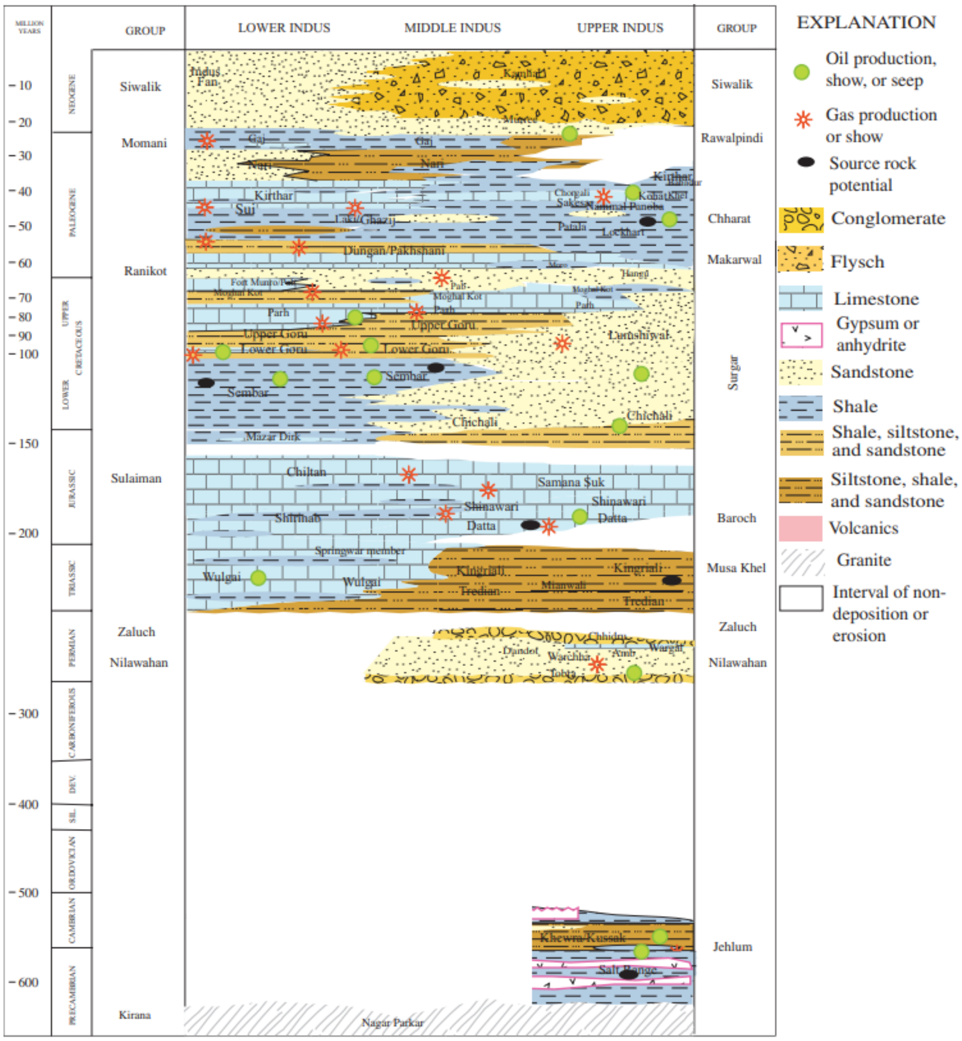

Fig 1: Stratigraphy & Oil and Gas potential of Indus Basin (Upper, Middle, Lower) (Wandrey et al., 2004)

4.1. Lower Goru Formation

Of Early Cretaceous, the Lower Goru Formation in the Lower Indus Basin is an important petroleum play. The lithology of the Lower Goru Formation is interbedded sandstone and shale, including subordinate siltstone and limestone. The sandstone is generally quartz-rich, and contains feldspar, lithic fragments, mica, glauconite, siderite, and iron oxides. Diagenetic processes led to the formation of carbonate cementation, and many clay minerals including kaolinite, illite, montmorillonite, and chlorite, all of which can impact reservoir quality. The Lower Goru Formation ranges in porosity, which is generally 5% to 30%, and variable permeability, with certain intervals generally exceeding 1 Darcy (Wandrey et al., 2004)

Hydrocarbon trapping in the Lower Goru Formation occurs by structural and stratigraphic trapping mechanisms. Structural traps are typically associated with, or bounded by faults, to create fault-bounded blocks- horsts and grabens and tilted fault blocks, all typical elements of the Lower Indus Basin extensional tectonic regime. Stratigraphic traps are important, usually as a result of pinch-outs of sandstones, facies changes in the formation, channel geometries and stratigraphic unconformities. The primary seal rock for Goru is the Upper Goru Formation which consists of shale and marl that act as a regional barrier sealing potential hydrocarbon migration. Intraformational shales in the Lower Goru can act as localized seals for specific sandstone reservoirs (Wandrey et al., 2004).

4.2. Pab Formation

The Pab Formation is also another important reservoir found in the Lower Indus Basin and belongs to the Late Cretaceous strata. The formation is lithological characterized by sandstone, while also including mudstone, shale, and less common arenaceous limestone. Sandstone form the dominant component of the Pab formation, quartz-rich sandstone, however the upper horizons contain basaltic lithic fragments indicative of a volcanic source and calcite cementation is common. Porosity is moderate to high at 10%-13% with variable permeability (Umar et al., 2015).

Hydrocarbon accumulation in the Pab Formation occurs in structural traps (e.g., trapped hydrocarbons along fault-bounded anticlines) and stratigraphic traps (facies changes and pinch-out of sandstone body). The seal rock in the Pab Formation differs with the position in the basin. The overlying Paleocene Ranikot Formation shales serve as a seal (Umar et al., 2015).

4.3. Sui Main Limestone

The Sui Main Limestone is an extremely prolific gas reservoir located within the Central Indus Basin and is classified as Early Eocene in age. The Sui Main Limestone's lithology is dominated by limestone, characterized as argillaceous to dolomitic carbonate, with thin shale marker beds and marl in the bottom part of the section. The primary mineral is calcite with some dolomite, and minor shale. The Sui Main Limestone displays good matrix and fracture-related porosity and a mixed permeability with some intervals displaying low permeability (Malkani & Malik, 2017).

Traps in Sui Main Limestone mainly consist of structural traps which are strongly related with anticlines and faults, and structural traps account for a large portion of Pakistan's total gas reserves. Hydrocarbons are also trapped stratigraphically in the Sui Main Limestone due to its lenticular development and the isolating properties of the surrounding shale. Formations of shale such as the Shaheed Ghat Formation, and the Ghazij Shale (Eocene) act as seals for the Sui Main Limestone (Ehsan et al., 2018).

4.4. Habib Rahi Formation

The age of the Habib Rahi Limestone in the Lower Indus Basin is Middle to Upper Eocene. Its lithology is composed mainly of limestone, often fossiliferous, and subordinate clay and marl. It is typically fine-grained, argillaceous limestone that may be highly fractured. The mineralogy is primarily calcite, with some areas containing dolomite and chert. The Habib Rahi Limestone contains good porosity, often enhanced by fracturing, and permeability is variable (Malkani & Malik, 2017).

Hydrocarbon trapping in this formation is attributable to structural features like anticlines and faults, as well as stratigraphic variations like facies changes. The Sirki Shale (Eocene) situated above the Habib Rahi Limestone can serve as a seal rock to the underlying limestone (Ehsan et al., 2018).

4.5. Lockhart Limestone

The Lockhart Limestone (Paleocene) is a carbonate-rich, primary and secondary porous unit located in the Upper Indus Basin that has potential as a hydrocarbon reservoir. Patala formation acts as seal for this formation. This formation may also be investigated in terms of its CO_2 storage capacity, particularly in areas of the resource where the hydrocarbon production has diminished (Meissner et al., 1973; Ahmad et al., 2025).

4.6. Ranikot Formation

The Ranikot Formation, which is Paleocene in age, represents another important petroleum play in the Lower Indus Basin. The lithology of the Ranikot Formation is typically sandstone with interbeds of shale and limestone and ranges from sandy in the east to shalier in the west. The mineralogy is quartzose sandstone with associated limestone and clay minerals found in the shale interbeds. Porosity in the Ranikot Formation is typically 20 % to 24 % and has a range of permeabilities (Ehsan et al., 2025).

In the Ranikot Formation, hydrocarbon traps are primarily structural, in association with anticlines and fault-related structures. Stratigraphic traps related to unconformities and facies changes also exist. The overlying Eocene Ghazij Shale is typically the seal rock for the Ranikot Formation, but much of the intraformational shales may also represent more localized seal (Ehsan et al., 2018).

4.7. Sakesar Formation

The Sakesar Formation is widespread within the Indus Basin and comprises Eocene limestone with secondary porosity due to fracturing. The presence of hydrocarbon-filled fractures indicates that it has reservoir qualities, and it has an average porosity of approximately 9%, but the permeability and connectiveness of bonds in the fracture system would require assessing for use with CO_2 storage. The Chorgali formation acts as seal for this formation (Shah et al., 2024).

4.8. Chorgali Formation

The Chorgali Formation, which is of Eocene age and located in the Upper Indus Basin, is dolomitic and does have primary and secondary porosity. The Murree Formation delineates it. The Chorgali Formation is a producing hydrocarbon reservoir, which has an average porosity of about 10%, but this formation provides another potential imaging of a target CO_2 to be held, especially in depleted fields (Waqas et al. 2024).

5. CO_2 Trapping Mechanisms in the Indus Basin

To safely and permanently store CO_2 in geological formations, it must be prevented from leaking via different trapping mechanisms. Trapping mechanisms can be broadly considered either physical or geochemical. The different geological settings of the Indus Basin fit into the potential for these trapping mechanisms.

5.1. Structural Trapping

This is the main mechanism, where CO_2 rises until it is trapped below an impermeable cap rock, such as shale or salt; since CO_2 is less dense than the formation fluids, it will keep rising. There are lots of structural traps in the Indus Basin and plenty of examples of where hydrocarbons have trapped using structural traps, and therefore injected CO_2 could be trapped as well. An example of structural traps is the Kadanwari Gas Field located in the Central Indus Basin, with a complex structural framework and numerous faults that compartmentalize the reservoir. There is plenty of potential for structural trapping of CO_2.

5.2. Stratigraphic Trapping

This happens when the rock type or permeability changes, providing a barrier for CO_2 flow. These traps can be depositional or formed through diagenetic changes. Because of the diversity of sedimentary environments in the Indus Basin, there would probably be many different types of stratigraphic traps. For example, lateral facies changes (within the Lower Goru Formation) could have created stratigraphic trapping situations.

5.3. Residual Trapping

As CO_2 displaces formation fluids, some CO_2 can become trapped in the pore spaces in disconnected ganglia due to the capillary forces. This form of trapping should be most effective in water-wet reservoirs. The sandstone-dominated formations in the Indus Basin (such as Lower Goru Formation) have the potential to have significant residual trapping. 4D X-ray tomography can observe this process at the pore scale as brine is displaced by CO_2 and the trapping of CO2 bubbles.

5.4. Solubility Trapping

CO_2 can dissolve into formation brine, resulting in denser brine that is less buoyant and reducing the likelihood of upward migration. The degree to which CO_2 can be captured by this method depends on several controllable variables, including pressure, temperature, and salinity of the brine. Deep saline aquifers located within the Indus Basin may be able to carry out this type of solubility trapping. The process of convective mixing will enhance the dissolution of CO_2 within a brine solution that exists within porous rock or sediment, and 4D X-ray tomography combined with analogue experiments, can be used to understand the extent of convective mixing with the brine.

5.5. Mineral Trapping

On longer timescales, dissolved CO_2 can react with minerals in the reservoir rock to form stable carbonate minerals, representing the most permanent form of storage. Even in carbonate-rich formations of the Indus Basin like Sui Main Limestone and Habib Rahi Formation, mineral trapping may be possible. 4D X-ray tomography can monitor mineral reactions through imaging the overall rock framework which can subsequently precipitate carbonate minerals over time, in the presence of a CO_2-saturated brine (Pearce et al., 2021).

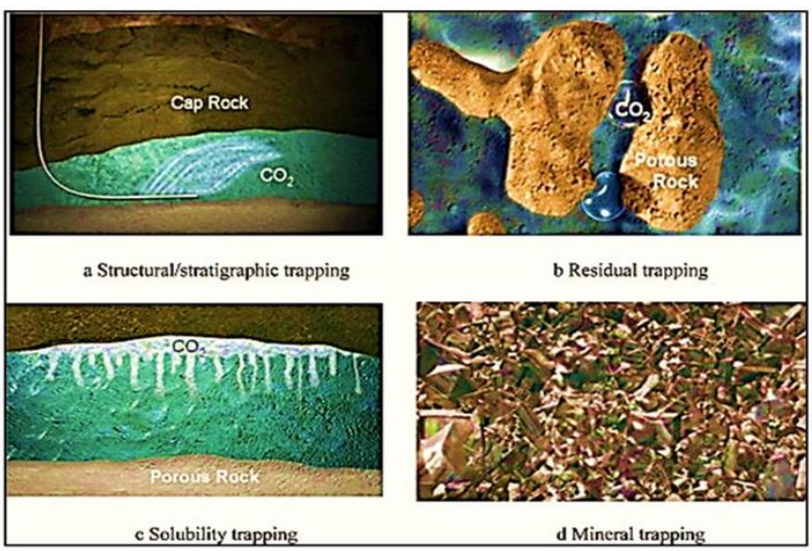

Fig 2: Schematic diagram illustrating key CO_2 trapping mechanisms: (a) structural/stratigraphic trapping, (b) residual trapping, (c) solubility trapping, and (d) mineral trapping. (Khan et al., 2024)

6. Comparison of Indus Basin reservoirs and global case studies

In order to assess the relevance of 4D X-ray tomography studies to the Indus Basin, a comparison of the lithological and petrophysical characteristics of reservoirs will be ideal. Taking the Lower Goru Formation as an example, whereas national studies have sandstones with lithology and porosity from as low as 5% up to 30% with low permeability (less than 1 Darcy), the Lower Goru Formation has a sandstone-dominated lithology with porosities reported from less (5%) to more than 30% and permeabilities greater than 1 Darcy in some cases (Wandrey et al., 2004). Similarly, carbonate formations in the Indus Basin such as the Sui Main Limestone, and Habib Rahi Formation can be compared with carbonate reservoirs from international case studies that focused on CO_2 mineralization (Yao et al., 2024).

Since 4D X-ray tomographic imaging methods have successfully been used to study CO_2 storage mechanisms in both sandstone and carbonate reservoirs internationally, this means it will most likely be highly feasible to utilize this imaging approach to understand CO_2 storage in specific formations in the Indus Basin. For example, core samples from Lower Goru Formation could be used to observe brine displacement by CO_2 in simulated reservoir conditions to examine the wetting and trapping behavior. The same could be done using 4D X-ray tomographic imaging approach on samples from the Sui Main Limestone to observe the potential carbonate mineral precipitation stimulated by CO_2.

Nonetheless, it is undoubtedly important to unpack the challenges and complexity associated with the reservoir that includes the Indus Basin. Quite a few of the formations have faults, considerable variation in lithological and petrophysical properties, and possibly elevated subsurface temperatures and pressures. All of these factors would be important to account for in the design and interpretation of 4D X-Ray tomography experiments on core samples. For example, it may be necessary for experimental designs to account for elevated pressures and temperatures, and in selecting core samples, it is preferable that they encapsulate the array of heterogeneities found in the reservoir.

Drawing on the findings of international case studies that suggest CO_2 can induce mineralization in carbonate reservoirs, it may be possible to identify pathways for additional enhanced CO_2 trapping by CO_2 induced mineralization in the carbonate-dominated formations found across the Indus Basin, such as Sui Main Limestone, Habib Rahi Formation, Lockhart Limestone, Sakesar Formation, and Chorgali Formation. Studies based on 4D X-Ray tomography could be designed to capture rates and extent of mineralization under a range of different conditions relevant to these formations, such as brine compositions and CO_2 partial pressures.

Evaluating caprock formations (e.g., Upper Goru Formation, Ghazij Shale, and possibly parts of the Ranikot Formation) in the Indus Basin is critical to reducing the risks associated with carbon storage. Evaluations on the physical and chemical integrity of caprocks, as demonstrated by many international published studies, could be excellent examples for future studies in the Indus basin. In these studies, researchers focused on the interaction of CO_2, shale, and other low-permeability rocks. While the 4D X-ray tomography was primarily designed to monitor the reservoir rocks, researchers could use 4D X-ray tomography to study the interaction of CO_2 and caprocks at the micro-scale. Studying the interaction of CO_2 and caprock composition may provide new insights into long-term sealing capabilities, including the potential for various leakage pathways.

7. Proposed Steps for Implementing 4D X-ray Tomography Studies in the Indus Basin

Conducting 4D X-ray tomography studies for carbon storage investigations in the Indus Basin would have a procedural methodology consisting of several important steps.

The first step will include careful selection and preparation of reservoir samples. This step must begin with identifying representative core samples from potential storage formations of interest, e.g., Lower Goru Formation or Sui Main Limestone, with the necessary geological logs, core descriptions, and possible other data in hand. These samples must represent the dominant lithologies, and range of porosity and permeability for the coatings target formation. After the samples have been selected, the core samples need to be prepared to a size and shape that meets the requirements of the size constraints in which the X-ray tomography instrument can obtain imaging (Bultreys et al., 2024). It is important to ensure that sample preparation does not alter the original pore structure of the reservoir rock through preparation methodologies to provide adequate imaging samples, like gentle coring and cleaning.

The next important step is to develop an experimental design for CO_2 injection. Experiments need to be constructed to faithfully reproduce the relevant reservoir conditions in the Indus Basin, such as the anticipated pressure, temperature and brine salinity for the formation being considered. There may be a need to use specialized pressure vessels or temperature control methods. Experimental protocols need to be developed to allow for CO_2 to be injected into the prepared samples at controlled rates and pressures to simulate potential injection scenarios in a field (Dai et al., 2025). There are options to test different rates and pressures to evaluate the effect on the flow behavior of the CO_2 and trapping efficiency for the samples from Indus Basin reservoir.

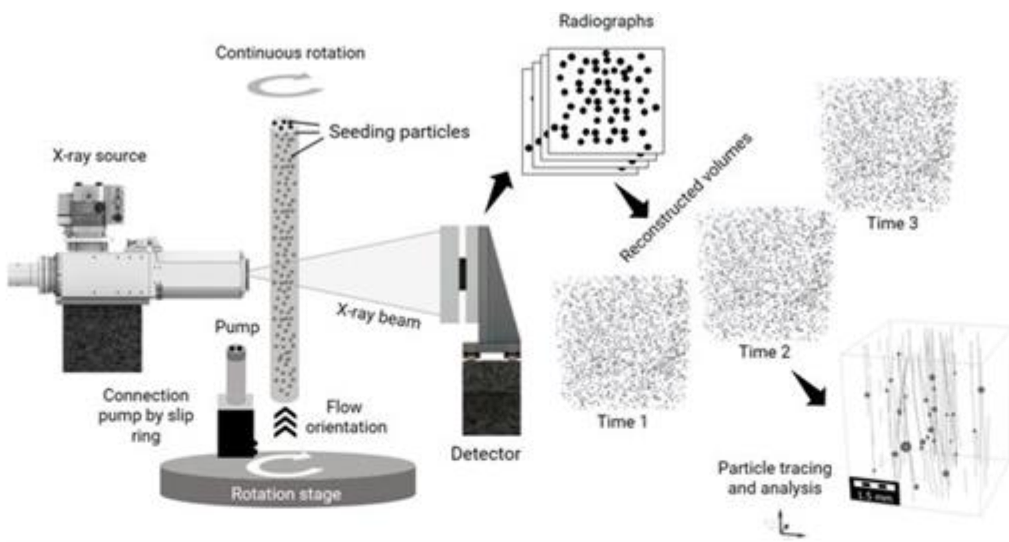

Fig 3: Overview of the experimental micro-CT setup. Continuous, high-speed rotation of the in situ device enables dynamic 4D reconstruction and particle trajectory tracking during CO_2 injection. (Mäkiharju et al., 2022)

Upon completing the protocols for sample preparation and experimental design, the data acquisition and processing will follow. Time-series images visualizing the CO_2 distribution and flow within the samples during and after the injection will be provided through high-resolution 4D X-ray tomographic instruments probably at synchrotron facilities (Bultreys et al., 2024). Acquisition parameters have to be fine-tuned for the specific sample to be observed, considering the required spatial and temporal resolution. The succeeding steps of raw tomography data acquisition were nevertheless defined by the application of various image processing methods used for enhancement of the image quality, segmentation of the various phases present (CO_2, brine, and rock matrix), and quantification of changes occurring across time. This may involve the use of special software and algorithms for noise reduction, image registration, and phase segmentation.

The last step analysis of results showcasing CO_2 distributions, dynamics in flow, and mechanisms of trapping would thus include analyzing acquired tomographic data. 4D tomographic data would thus form the basis for analyzing the space and time distribution of CO_2 within the pore space of the Indus Basin reservoir samples. This will provide direct evidence of the ways in which CO_2 migrates and accumulates within the rock. That data would also allow for quantification levels of CO_2 saturation and also show the dominating trapping mechanisms (Dai et al., 2025). This may also include looking at the relative contributions from structural trapping (when the sample has a particular geometry), residual trapping (where CO_2 is retained through capillary forces), solubility trapping (where the gas is dissolved in brine), and perhaps mineral trapping (formation of carbonate minerals). Finally, a comparison will be done for the obtained 4D X-ray tomography data across different time points, probing how CO_2 injection has affected the porosity, permeability (from changes in pore connectivity), and mineralogy of the Indus Basin reservoir samples as time goes by in terms of any evidence for dissolution or precipitation of minerals (Pearce et al., 2021).

8. Future Directions

Future studies should use 4D X-ray tomography with the aim of better understanding uncertainties and identifying optimal strategies for carbon storage within the Indus Basin. Studies should be performed on additional reservoir formations other than Lower Goru and Sui Main Limestone in order to better understand the overall CO_2 storage capacity of the Indus Basin. The next stage of investigation should investigate formations such as Habib Rahi, Lockhart, Ranikot, Sakesar, and Chorgali Formations where we can characterize both their storage capacity and limitations. Because of the inherent geological complexities of Indus Basin reservoirs, future studies should also investigate the impact of the reservoir heterogeneity on the CO_2 flow and trapping. High-resolution 4D X-ray tomography lends itself well to investigating the impact of natural fractures, sedimentary laminations, and clay mineral presence on CO_2 migration and trapping in the pore space of the Indus Basin formations.

To evaluate the viability and safety of carbon storage in the long term, it is critical that the long-term fate of stored CO_2 is assessed. Long-duration 4D X-ray tomography projects in the Indus Basin, through monitoring of CO_2 behavior in samples taken from the reservoir over time. is a promising avenue for future research. These modalities of study will enable an effective assessment of leakage or potential migration, and importantly, the long-term stability of the stored CO_2 in particular geological formations.

It also seems promising to progress these detailed pore-scale data from 4D X-ray tomography and connect them to larger-scale basin reservoir modelling and geophysical monitoring approaches. Future studies should attempt to encompass these different scales of observation, to develop, calibrate, and validate reservoir models from microtomography data, and help to calibrate geophysical data acquired at the field scale, for example, seismic and electrical resistivity tomography.

Lastly, the possibility of improved hydrocarbon recovery (EOR) using CO_2-injection in Indus Basin oil reservoirs represents a chance to have both carbon storage and oil production increase occur simultaneously. Future studies using 4D X-ray tomography could investigate CO_2-EOR efficacy in appropriate Indus Basin reservoirs by optimizing injection conditions to maximize hydrocarbon recovery and CO_2 stored in the formation.

9. Conclusion

4D X-ray tomography serves as an important and powerful tool for enhancing the understanding and development of geological carbon storage in the Indus Basin, Pakistan. Its unique capabilities for visualizing and quantifying the behavior of CO_2 in the pore space level, is critical to study the essential processes that control storage mechanisms, long-term fate, and possible effects on reservoir properties. The safe and effective operation of carbon storage projects in Pakistan will rely on thorough reservoir characterization and good monitoring. 4D X-ray tomography can deliver an effective support to the thorough characterization at a fundamental level. Future research efforts should primarily be focusing on using new imaging methods, such as 4D X-ray tomography, to reduce important uncertainties associated with storing CO_2 in the diverse geological formations in the Indus Basin. This will help develop more effective storage strategies and promote a better understanding of subsurface CO_2 behavior. These research efforts can further aid Pakistan's climate change mitigation goals and energy future direction.

10. References

[1] Ahmad, M., Tanoli, U. F., Umar, M., Ahmad, T., & Ahmed, A. (2025). *Shallow-marine Late Thanetian Lockhart Limestone from the Hazara Basin, Pakistan: Insights into foraminiferal biostratigraphy and microfacies analysis.* Geosciences, 15(2), 63. https://doi.org/10.3390/geosciences15020063

[2] Ahmed, S., Habib, W., Ali, I., Nazeer, A., & Ahmad, S. (2024, March). *Business model and feasibility of carbon capture and storage in depleted fields and large subsurface geological sites in Pakistan*. Paper presented at the SPE/AAPG/SEG Carbon, Capture, Utilization, and Storage Conference and Exhibition, Houston, TX, United States. https://doi.org/10.15530/ccus-2024-4014411

[3] Aziz, P. A., Marhaendrajana, T., Nurhandoko, B. E. B., & Siagian, U. W. R. (2025). *Time-Dependent CO2-Brine-Rock interaction effect on sand onset Prediction: A case study of Dolomite-Rich sandstone in Air Benakat Formation, South Sumatra, Indonesia.* ACS Omega. https://doi.org/10.1021/acsomega.4c09499

[4] Bultreys, T., Ellman, S., Schlepütz, C. M., Boone, M. N., Pakkaner, G. K., Wang, S., ... & Cnudde, V. (2024). *4D microvelocimetry reveals multiphase flow field perturbations in porous media.* Proceedings of the National Academy of Sciences, 121(12), e2316723121. https://doi.org/10.1073/pnas.2316723121

[5] Bultreys, T., Ellman, S., Schlepütz, C. M., Boone, M., Pakkaner, G. K., Wang, S., Borji, M., Van Offenwert, S., Moazami Goudarzi, N., Goethals, W., et al. (2023). *4D X-ray micro-velocimetry data of multiphase flow perturbations in porous media.* Paul Scherrer Institute (PSI). https://doi.org/10.16907/C0DFA6C8-25DA-454E-82FA-FC5DB7F7C6F2

[6] Cooper, M. P. (2023). *4D tomography reveals a complex relationship between wormhole advancement and permeability variation in dissolving rocks.* Advances in Water Resources, 175, 104407. https://doi.org/10.1016/j.advwatres.2023.104407

[7] Dai, K., Xia, Y., Yuan, G., Liu, T., Zhang, H., Song, H., & Yuan, H. (2025). *Experimental procedures, influencing parameters, and future prospects of geological sequestration of carbon dioxide*. Frontiers in Earth Science, 13, 1442518. https://doi.org/10.3389/feart.2025.1442518

[8] Ehsan, M., Chen, R., Ali, M., Manzoor, U., Naqvi, S., Ali, A., Hussain, M., Abdelrahman, K., & Ullah, J. (2025). *Evaluating the Ranikot Formation in the middle Indus Basin, Pakistan as a promising secondary reservoir for development*. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 11, 10. https://doi.org/10.1007/s40948-025-00950-6

[9] Ehsan, M., Gu, H., Akhtar, M. M., Abbasi, S. S., & Ehsan, U. (2018). *A geological study of reservoir formations and exploratory well depths statistical analysis in Sindh Province, Southern Lower Indus Basin, Pakistan.* Kuwait Journal of Science, 45(2). https://journalskuwait.org/kjs/index.php/KJS/article/view/3290

[10] Fentaw, J. W., Emadi, H., Hussain, A., Fernandez, D. M., & Thiyagarajan, S. R. (2024). *Geochemistry in geological CO_2 sequestration: A comprehensive review.* Energies, 17(19), 5000. https://doi.org/10.3390/en17195000

[11] Jangda, Z., Menke, H., Busch, A., Geiger, S., Bultreys, T., & Singh, K. (2024). *Subsurface hydrogen storage controlled by small-scale rock heterogeneities.* International Journal of Hydrogen Energy, 60, 1192–1202. https://doi.org/10.1016/j.ijhydene.2024.02.233

[12] Khan, M. N., Siddiqui, S., & Thakur, G. C. (2024). *Recent advances in geochemical and mineralogical studies on CO_2–brine–rock interaction for CO_2 sequestration: Laboratory and simulation studies.* Energies, 17(13), Article 3346. https://doi.org/10.3390/en17133346

[13] Mäkiharju, S. A., Dewanckele, J., Boone, M., Wagner, C., & Griesser, A. (2022). *Tomographic X-ray particle tracking velocimetry: Proof-of-concept in a creeping flow.* Experiments in Fluids, 63(1), Article 16. https://doi.org/10.1007/s00348-021-03362-w

[14] Malkani, M. S., & Malik, Z. (2017). *Stratigraphy of Pakistan*.

[15] Meissner Jr., C. R., & Rahman, H. (1973). *Distribution, thickness, and lithology of Paleocene rocks in Pakistan*. U.S. Government Printing Office. https://pubs.usgs.gov/publication/pp716E

[16] Noiriel, C., & Renard, F. (2022). *Four-dimensional X-ray micro-tomography imaging of dynamic processes in geosciences.* Comptes Rendus Géoscience, 354, 255–280. https://doi.org/10.5802/crgeos.137

[17] Pearce, J. K., Dawson, G. K. W., Sommacal, S., & Golding, S. D. (2021). *Micro CT and experimental study of carbonate precipitation from CO_2 and produced water co-injection into sandstone.* Energies, 14(21), 6998. https://doi.org/10.3390/en14216998

[18] Shah, S. B. A., Ismail, K., & Bakar, W. Z. W. (2024). *Integrated analysis of the Eocene Sakesar Formation: Depositional environment, microfacies, geochemistry, and reservoir characteristics in the Potwar Basin, Pakistan.* Earth Sciences Research Journal, 28(1), 17–27. https://doi.org/10.15446/esrj.v28n1.107766

[19] Shah, S. Y., Du, J., Kazmi, S., Du, L., Khan, U., Zhang, B., & Tan, J. (2024). *Integrated three-dimensional structural and petrophysical modeling for assessment of CO_2 storage potential in gas reservoir.* Lithosphere, 2024, Article 222. https://doi.org/10.2113/2024/lithosphere_2024_222

[20] Umar, M., Khan, A. S., Kelling, G., Friis, H., & Kassi, A. M. (2015). Reservoir attributes of a hydrocarbon-prone sandstone complex: case of the Pab Formation (Late Cretaceous) of Southwest Pakistan. Arabian Journal of Geosciences, 9(1). https://doi.org/10.1007/s12517-015-2170-3

[21] Wandrey, C.J., Law, B.E., Shah, H.A., (2004). Sembar Goru/Ghazij composite total petroleum system, Indus and sulaiman-Kirthar geologic provinces, Pakistan and India. U. S. Geol. Surv. Bull. 23, 2208-C

[22] Waqas, A., Naseem, S., & Hussain, M. (2024). *Accentuating the reservoir potentials of Balkassar field by delineating the fracture trends and hydrocarbon prospects with the aid of seismic attributes. ACS Omega, 9*(25), 27047–27064. https://doi.org/10.1021/acsomega.4c00191

[23] Yao, J., Chen, Z., Jiang, C., & Peng, X. (2024). *An integrated numerical study of CO_2 storage in carbonate gas reservoirs with chemical interaction between CO_2, brine, and carbonate rock matrix*. Applied Sciences, 14(14), 6002. https://doi.org/10.3390/app14146002

[24] Yashiro, W., Voegeli, W., & Kudo, H. (2021). *Exploring frontiers of 4D X-ray tomography*. Applied Sciences, 11(19), 8868. https://doi.org/10.3390/app11198868

[25] Yousaf, H. (2020). *Depositional settings of Cretaceous rocks in Central Indus Basin of Pakistan: A review*. GeoConvention 2020. Retrieved from https://geoconvention.com/wp-content/uploads/abstracts/2020/53149-depositional-settings-of-cretaceous-rocks-in-centr-01.pdf

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The authors declare that there are no conflicts of interest regarding the publication of this article.

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