Integration of Seismic Characterization & Petrophysical Analyses to assess Carbon Storage Potential in Saline Aquifers: A Case Study from Tapti-Daman Area, Mumbai Offshore Basin

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Abstract

It is conspicuous that industrialization has impacted our climate and almost every nation has a role to play in it. With rising global temperatures and increased concentrations of Carbon-dioxide (CO_2) in the atmosphere, it is our responsibility to impede the gradual obliteration of the climate. Carbon Capture & Storage (CCS) is one of the ways in which mankind can contribute to climate reversal or at least sustain rising temperatures. In this regard, the assessment of Carbon Storage sites is pivotal and in our present study, an integrated approach has been deployed to not only identify the storage site but also to estimate the volume of CO_2 that can be sequestered into the subsurface. Such integrated assessment has been carried out for the first time in Mumbai Offshore Basin, making it a potential site for a Carbon sink.

Introduction

The CO_2 levels in the atmosphere are rising at an alarming rate and have been a grave concern for environmentalists and world leaders. To mitigate this severe increase in CO_2 concentration in the atmosphere, 190+ countries with their leaders signed Paris Climate Agreement (PCA) in 2015, where a target was set to constrain the global temperature rise to 2 degrees Celsius above the pre-industrial levels (United Nations Climate Change, 2015). In accordance with the objectives of PCA, the Intergovernmental Panel on Climate Change (IPCC) declared a Carbon Budget of 2900 Gt, which limits the total CO_2 emissions. The IPCC contemplates that Carbon Capture and Storage (CCS) have a pertinent role to play in reversing climate change. Though there are many active projects around the world sequestering 300 Mt of CO_2 cumulatively (Loria and Bright, 2021), this figure is abysmal compared to the required estimate of 27 Gt of CO_2 to be stored in the geologic formations by 2050 (Zoback and Gorelick, 2012).

India has pledged to reduce its Carbon emissions by 33-35 % by 2030 from the CO_2 concentration of 2005. Thus, the primary concern for the energy industry operating in India is to decarbonise their operations and explore the possibility of CO_2 storage potential of various geologic formations across all 26 sedimentary basins and assess their efficiency in holding large volumes of CO_2. Oil fields (preferably depleted) are a preferred site for CCS as the capital-intensive installations exist in close proximity which will eventually aid in CO_2 storage. Oil fields also provide the geological data and other reservoir properties of the formations which otherwise are scarce in other areas.

In the present study, we are assessing the CO_2 storage potential of the Tapti-Daman Area in the Mumbai Offshore field as the area is rife with porous reservoirs of sandstones and the depth at which the reservoir is encountered is not too shallow. The storage potential of the reservoir, and the sealing capacity of the trap, validated with seismic & petrophysical analyses have been carried out in detail. This study is an attempt to aid in the cleansing of the environment and align the nation with the objectives of decarbonisation in accordance with the PCA.

General Geology

Mumbai offshore basin is an extensional passive margin basin in the western continental margin of India which extend offshore up to 200 m isobath. Tapti Daman Block, one of the 6 tectonics blocks of Mumbai Offshore Basin lies towards the North-Eastern side, and covers an area of 27,000 SKM (Figure 1a). In the Tapti-Daman area, the major tectonic trend active is the Dharwarian trend (NNW-SSE) which is dominant on the southern side. Major lows like Dahanu, Purna, Navsari and structures like B12, C26, C24, South, Mid and North Tapti etc. are the major established

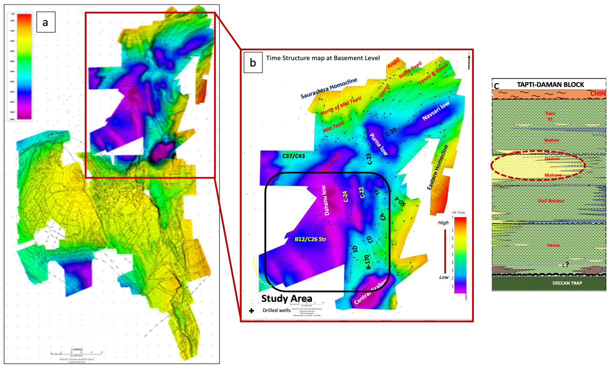

Figure 1: a) Time Structure Map at Basement top in Mumbai Offshore; b) Time Structure Map at Basement Top in Tapti-Daman Block; c) General Stratigraphy of Tapti-Daman Block

fields in the Tapti Daman Block. The area is the transition between pure clastic Cambay Basin and pure carbonate Mumbai Offshore Basin (Figure 1b). The major reservoir encountered in the Tapti Daman Block is the Oligo-Miocene clastics of the Mahuva, Daman and Mahim Formations. Panna Formation of Late Paleocene to Early Eocene age is considered as an effective source rock (Figure 1c). Strati-Structural and structural entrapment in the form of fault-bounded nose, structural paleo highs and Inversion structures are the major locales for hydrocarbon exploration.

The study area is identified towards the southern side of the Tapti Daman Block (55-60 km from the coast) with an area of 4000 SKM, comprises of a major part of Dahanu Low and paleo highs of B12, C26, C24, C23, CA, CD, SD etc. The study area has dominantly coarser clastics in the Late Oligocene Daman Formation with minor development of sandstone facies observed in the Early Oligocene Mahuva Formation towards the NE side. In the present study, a thorough analysis was carried out in Daman Clastics to assess its potential for future CO_2 storage.

Sandstones are one of the effective storage complexes for CO_2 sequestration compared to carbonate reservoirs because of their stability against any reactive agents. In contrast to it, for carbonate facies, it is very difficult to assess the potential for CO_2 storage because of its reactive nature. As the entire Mumbai Offshore dominantly has Carbonate reservoirs with sparse distribution of clastics in few stratigraphic units except the Oligo-Miocene clastics of Tapti Daman Block, our focus of the study is constrained within the clastics of the Tapti Daman area.

Methodology

The study has been pursued based on the availability and integration of various data sets comprising Geological reports, Log data of key wells falling in the study area, and 3D (Pre-stack Time Migrated) PSTM Seismic Data (Both Full stack and Angle Stacks). A comprehensive geological fathoming is pertinent in order to establish the presence of reservoir, seal and entrapment necessary for the storage of CO_2. The 3D PSTM data is perused and analyzed thoroughly for structural configuration and facies characterization while the amplitude information from far-angle stacks has provided us with the distribution and areal extent of the reservoir sands. The sealing effectiveness and caprock integrity have been studied in detail by calculating the brittleness index and the pore-size distribution corresponding to the shale and sandstone of Late Oligocene deposits. Consequently, the evaluation of volumetric capacity has aided in inferring the Carbon Storage potential of the study area.

Results & Discussions

Potential of Late Oligocene CO_2 storage complex

Wellbore penetrated within Daman formations are taken as the constraints and data point for assessing the potential of the storage aquifer. Daman Formation consists of multi-stack coarsening and box-type sandstone units intercalated by thick shale in between. Log character shows a uniform distribution of sandstone throughout the study area with similar quality reservoir (Figure 2a). The sand units are tidal channel and bar complexes, reworked and deposited by tidal current (Figure 2c).

The gross reservoir thickness varies from 250 to 550 m and sandstone thickness varies from 40 to 80 m in the entire Daman Formation. The top seal is characterized by thick marine shale of the Early

Miocene Mahim Formation intercalated with thin limestone bands. The thickness of the seal varies from 300 m to 500 m The thick impervious shale is expected to provide sufficient barrier to retain the buoyant fluid to escape to the surface (Figure 2a & b).

The study area is a broad low with isolated paleo highs in between. The paleo highs like B12, C24, C23 etc. are accentuated in the successive younger tectonics. A series of narrow highs and lows (CA, CD, SD) can be observed towards the eastern side which is proven to be porous. The fault pattern at the Daman level indicates that the intensity of faulting is very minimal in the study area, thus suggesting potential storage. (Figures 3 & 4).

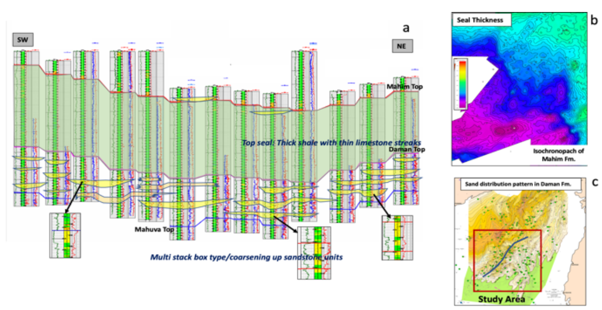

Figure 2: a) Log correlation through NE-SW direction showing sand distribution pattern and seal thickness; b) Isochronopach map of Mahim Formation (thickness variation 200-500 m) showing seal thickness; c) Sand isolith map of Daman Formation in Tapti Daman Block

Structural & Seismic Amplitude Characteristics

3D PSTM volume is used for a comprehensive understanding of the structural attributes of the study area. Structural discontinuities were mapped on time slices and vertical sections based on their seismic characteristics and expressions. Semblance-based discontinuity slices extracted along key seismic markers mathematical assessment of were incorporated in the study which permits the seismic data without being biased by manual interpretation.

Figures 5a & b are the uninterpreted and interpreted horizon slices that depict the spatial distribution of faults in the Mahim Formation. One of the positive indicators of sealing formation property is to have good lateral continuity i.e. stratigraphically uniform

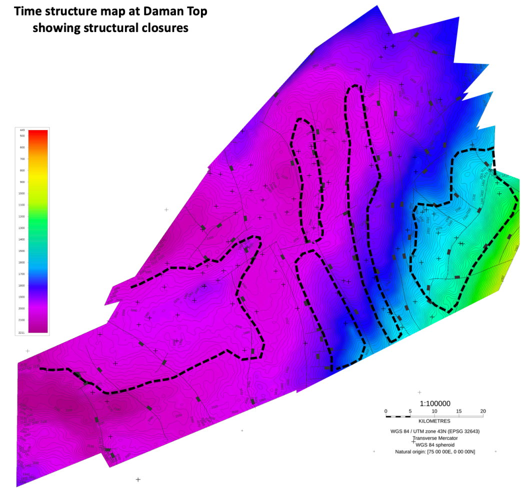

Figure 3: Time structure map at Daman Formation showing structural closures available in the study area

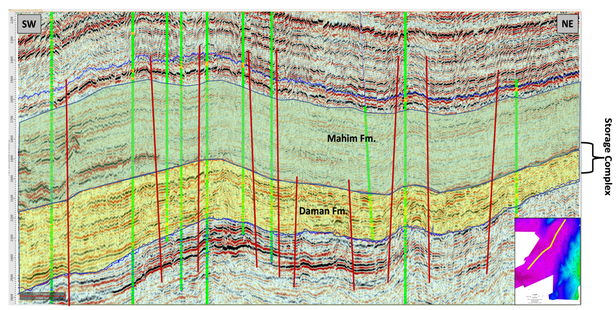

Figure 4: Seismic section showing the storage complex and fault pattern in the study area

with small faults (Delprat-Jannaud et al., 2013). This is also evident from Figure 4 which represents a seismic line traversing the study area exhibiting the disposition of faults, showing good continuity.

Reflection amplitudes were studied on the Far-Angle Stack of the 3D PSTM Seismic data. Since, strong reflection amplitudes correspond to lithologies having higher porosities (Chopra and Marfurt, 2005), the study has been aligned on the same principle, where Root Mean Squared (RMS) amplitudes are extracted at various seismic markers which correspond to different geological times. RMS amplitude is preferred over a myriad of amplitude-derived attributes as RMS further diminishes the low amplitude values and magnifies the higher ones. The RMS slice within the shale interval (above Daman) which is perceived to act

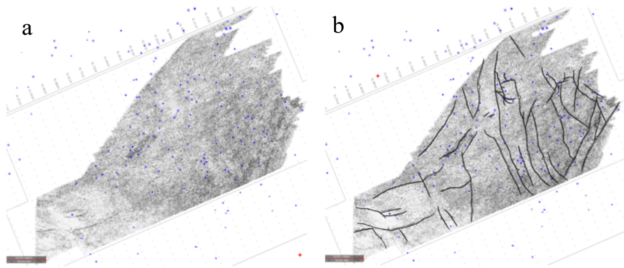

Figure 5: Discontinuity slices extracted along a horizon corresponding to Mahim Formation. a) Un-interpreted; b) Interpreted

as a seal, shows extremely low amplitude (Figure 7a). The lithology is also consistent throughout the study area, implying a uniform distribution of the same lithology, laterally, devoid of any lithological barrier. Figure 7b depicts the presence of porous sandstones underlying the non-porous shale, deposited in a deltaic environment. These porous deposits are observed as high amplitude channel geometry features on slices in an otherwise low amplitude background.

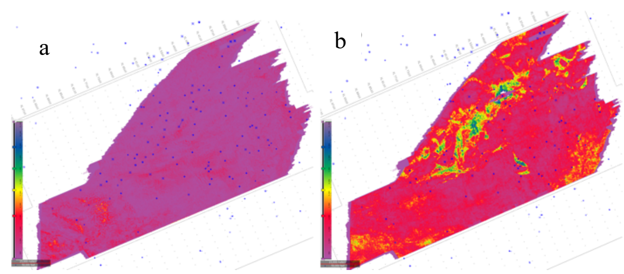

Figure 6: RMS Amplitude slices with analysis window corresponding to a) shale of Mahim Formation; b) stack of sands of Daman Formation

To validate and characterise the distribution of facies in the study area, a model-based inversion is carried out on the stacked seismic data, incorporating sonic and density logs of 12 wells. The inversion analysis window constrained the vertical extent of the Daman sandstones and its overlying shales of Mahim formation. A vertical section (Figure 7a) passing through well C-24-XX show the presence of a porous sandstone reservoir, characterised by higher acoustic impedance values which could ideally serve as a CO_2 sink. Overlying, Daman formation, 300-500m thick shale characterised by low acoustic impedance values could serve as the seal required to trap the sequestered CO_2. The well-based cross-plot between P-Impedance (Acoustic) and Neutron derived porosity, with Gamma Ray log as the colour variable, aids in distinguishing the reservoir from seal and validate the presence of porous sandstone facies of Daman formation with the overlying shales of Mahim formation. The neutron porosity of Daman sands lies in the range of 15-42% with effective porosity >20% as indicated by the petrophysical analyses (Figure 7b).

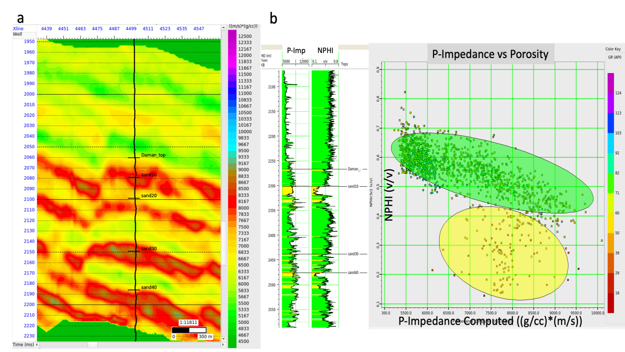

Figure 7: a) A P-Impedance section passing through the well C-24-XX depicting the multiple stacks of coarser clastic (sand). b) Well based Cross-plot for well B-12-XX of P-Impedance vs Porosity, differentiating sandstones of Daman Formation from the shale dominant Mahim formation

Sealing Capacity: Brittleness Analysis

The sealing capacity of cap rock plays a pivotal role in CO_2 storage. The brittleness of the cap rock can provide insights into its sealing capacity.

Geomechanical analysis of a well from C-24 structure in the study area, shows a brittleness index of 20-30 units, while the sandstone reservoir exhibits higher brittleness (50-60 units) (Figure 8). Lower brittleness of shale indicates greater ductility and plastic deformation under stress. This implies that shale is more likely to deform instead of fracturing when subjected to pressure, improving its sealing capacity by closing small fractures or pathways and reducing CO_2 migration potential. Moreover, fine-grained matrix of shale with smaller pore sizes compared to sandstone results in lower permeability, restricting fluid flow, including CO_2.

Sealing Capacity: Analysis of NMR-based Pore Size Distribution

The analysis of pore size distribution based on the T_2 relaxation time distribution shape provides valuable insights into the suitability of a sandstone reservoir and its overlying shale formations for CO_2 storage. In the case of Well C-24-XX, the storage sandstone exhibits a broad T_2 distribution with a wide range of relaxation times, indicating the presence of diverse pore sizes (Figure 9). This suggests that the sandstone has the potential to store and facilitate the flow of CO_2 within its pore network. In contrast, the overlying and underlying shale formations exhibit a unimodal peak at a lower relaxation time, indicating a more uniform distribution of smaller pore sizes. This indicates that the shale formations possess the required sealing capacity and lower permeability, which reduces the risk of CO_2 migration.

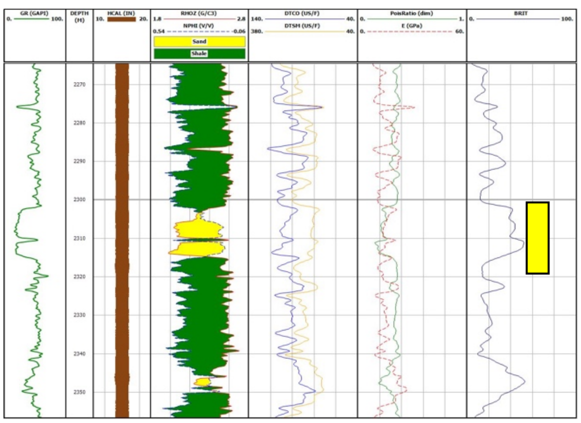

Figure 8: Wireline logs of well C-24-XX with Computed Brittleness Index/Sealing Capacity for CO_2 storage

Volumetric Estimation

The storage capacity estimation can be elusive as many assumptions and simplified models are made to infer the total volume. Such calculations mainly involve the estimation of the available pore space volume and the fraction of pore space accessible to CO_2. This fraction is dictated by the storage efficiency. The cumulative estimates of the CO_2 storage capacity around the world vary between 100-100000 Gt of CO_2 (Bradshaw et al., 2007). Whereas, pertaining to India, the estimates are in the range of 47-572 Gt of CO_2 (Viebahn et al., 2014). The total Basin estimate for Mumbai Offshore is inferred to be 9.26 Gt of CO_2 storage capacity (Vishal et al., 2021).

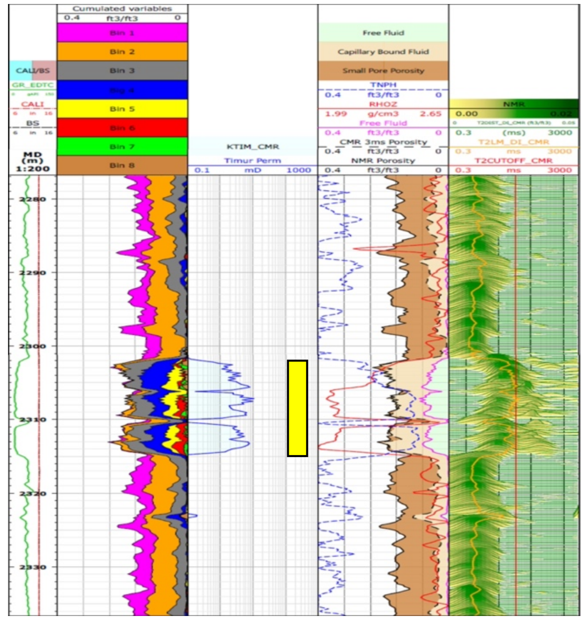

Figure 9: Processed NMR log response against the potential CO_2 reservoir and the underlying and overlying shale

However, this study is carried out in a limited area of the Tapti-Daman block, to estimate the volumetric storage potential of CO_2 and the calculations are done in accordance with the guidelines of SPE's PRMS scheme. The storage efficiency coefficient, (which determines the fraction of pore space accessible to CO2) used to calculate the total Mass of CO2 is 0.015 (Vishal et al., 2021).

A volumetric calculation method which can derive the effective mass of CO_2 sequestered under ideal conditions is given as (Goodman et al., 2011)

$$\text{Total } M_{CO_2} = \rho_{CO_2} A\, h\, \varphi \quad (1)$$

$$\text{Effective } M_{CO_2} = \rho_{CO_2} A\, h\, \varphi\, \varepsilon \quad (2)$$

where M_{CO_2} is the Mass of CO_2 sequestered, ρ_{CO_2} is the density of CO_2 in the supercritical state, taken as 0.7 g/cc (Haghbaksh et al., 2013) A and h are the area and average thickness of the reservoir respectively, φ is the average pore fraction in the field, ε is the storage efficiency coefficient. ε is essential in the calculation as the reservoir heterogeneity, capillary force, fluid viscosity and gravity affect the transverse & longitudinal distribution of CO_2 in a reservoir.

	Area (SKM)	Thickness (m)	Porosity (%)	Total Capacity (Metric ton)	Effective Capacity (Metric ton)
P10	880	60	25	9240	138.6
P50	720	50	20	5040	75.6
P90	560	40	18	2822	42.3

Table 1: Estimated parameters and the quantification of Total and effective capacity of aquifers in the study area. The areal extent is indicated in Figure 10

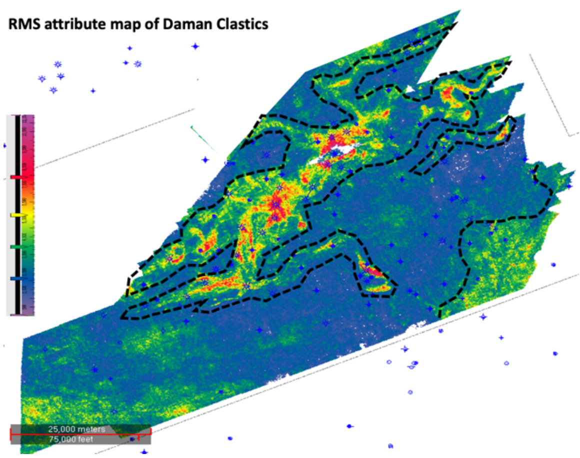

Figure 10: RMS Attribute Slice corresponding to the sands of Daman Formation. The areal extents have been calculated on this map

Conclusion

The present study has given us an insight into the potential of Carbon Capture Storage in the Tapti-Daman Area of Mumbai Offshore. An integrated study has aided in the quantification of volume that can be effectively stored in the aquifer. As the depth is in the median range, the pressure in the Daman formation is hydrostatic and the temperature varies in the range of 90-120 degrees Celsius, which makes it a very conducive storage site for CO_2. The porosity is more than 20% with the permeability of the aquifer greater than 0.3 D. The seal is also very effective owing to its thickness and low brittleness. Excellent lateral continuity and the presence of minimal faults with small throws make this area extremely promising for a Carbon sink.

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