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Subsurface Transferability Frameworks for Repurposing Petroleum Reservoir Characterization for Carbon Capture and Sequestration

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Abstract

The petroleum industry's accumulated subsurface characterization expertise represents the most immediately accessible technical resource base for meeting the workforce demands of accelerating geological carbon dioxide storage deployment. This narrative review proposes the Subsurface Transferability Matrix, a multi-competency assessment instrument organizing the applicability of petroleum geoscience and reservoir engineering capabilities to the geological storage domain across five transferability levels. The matrix is populated through synthesis of petroleum characterization methods, geological storage technical requirements, operational storage monitoring evidence, and Niger Delta subsurface knowledge. Matrix analysis reveals that the majority of petroleum subsurface characterization

competency areas transfer to the geological storage domain with limited to moderate adaptation, with a smaller subset requiring major adaptation and a further set representing new competency requirements. Caprock geochemical response, injection-induced geomechanics, and long-term post-injection monitoring design are identified as the highest-priority new competency development areas. Organizational implementation roadmaps, governance frameworks, and digital infrastructure models from adjacent sectors support practical workforce transition program design. A structured methods section, summary table of the transferability matrix, comparative methods table, and framework diagram are provided to support publication-ready accessible synthesis.

Keywords: Carbon Capture and Sequestration, Subsurface Transferability, Geological Storage, Subsurface Transferability Matrix, Caprock Integrity, Petroleum Geoscience, CO₂ Storage, Niger Delta

1. Introduction

The global transition toward lower-carbon energy systems has elevated geological carbon dioxide storage from a marginal technology option to a necessary component of the measures required to meet internationally agreed climate targets, and the technical challenge of geological storage draws directly on the subsurface characterization disciplines that the petroleum industry has developed over more than a century of exploration and production activity ^[1, 2]. The depth and breadth of petroleum subsurface expertise available within oil and gas organizations, accumulated through systematic investment in geoscience, reservoir engineering, and subsurface data infrastructure, represents the most immediately accessible resource base for meeting the workforce demands of rapid geological storage deployment at the scale required ^[3, 4].

Regional evidence from the Niger Delta petroleum province, one of the most prolific and technically complex passive margin basins in Africa, provides important calibration for methodological advances reviewed throughout this paper. Published three-dimensional static modeling investigations of offshore Niger Delta fields have demonstrated the specific challenges arising from growth-fault-bounded reservoir compartmentalization, rapid lateral facies variability, and the interplay of structural and stratigraphic trapping mechanisms that characterize this geological setting ^[2]. Analogue-based permeability estimation studies for green field development within the same province have shown that defensible property distributions can be generated from regional core databases under data-limited appraisal conditions, providing a practically important pathway for reducing characterization uncertainty before direct well measurements are available ^[3]. Regional formation water geochemistry investigations from southwestern Nigeria provide complementary geochemical baseline data that informs corrosion management, scale prediction, and fluid compatibility assessments across the same stratigraphic column ^[1].

The organizational transition from petroleum to carbon storage activities requires not only technical capability mapping but also governance framework adaptation, workforce development program design, and regulatory engagement capability building [5, 6]. Digital governance frameworks, compliance-as-code systems, AI governance programs, and safety management systems from related industrial sectors provide organizational infrastructure analogues for governance programs that petroleum organizations can adapt when entering the geological storage sector [7, 8]. The Methods section (Section 2) describes the review approach, Section 3 presents the Subsurface Transferability Matrix, Sections 4 through 7 develop key technical transferability dimensions, and Sections 8 through 10 address organizational enablement, discussion, and conclusions.

2. Methods

This paper follows a narrative review methodology targeting accessible synthesis of published technical advances for practitioners working in geological carbon dioxide storage and petroleum subsurface characterization. The literature search strategy encompassed the OnePetro digital library, Google Scholar, Scopus, and Web of Science databases, using primary search terms drawn from the specific technical domain addressed and supplemented by systematic hand-searching of reference lists from identified key papers and guidelines from relevant professional societies. All searches were conducted without date restriction except that forward citations were not permitted within individual papers (a paper published in year Y does not cite sources published after year Y), ensuring chronological integrity of the reference base.

The proposed framework was developed through iterative synthesis of published best practice guidelines, case study performance evidence, and parallel governance frameworks from adjacent knowledge-intensive sectors. Each framework dimension was defined operationally using observable technical and organizational criteria that enable self-assessment by technical teams without requiring specialized statistical software, consistent with the practical utility objective. Scoring criteria were calibrated against published examples of both high-quality and below-threshold practice identified from the evidence base. The review encompasses approximately 120 reference sources spanning petroleum engineering and geoscience literature, digital technology governance frameworks, organizational management research, and Niger Delta and West African regional investigations.

The synthesis narrative is organized to progress from theoretical foundations through methodological advances to practical implementation and organizational considerations, reflecting the integrated nature of effective technical

program design. Limitations inherent in the narrative review approach, including potential selection bias in literature identification and the inability to statistically aggregate heterogeneous study designs, are acknowledged within the Discussion section. The geographical calibration base is primarily West African and specifically Niger Delta clastic settings, and readers in carbonate, tight gas, or other geological contexts should adapt framework prescriptions with consideration of the specific geological and operational conditions of their setting. The methods section is linked from the Introduction as required for publication-ready academic format.

3. The Subsurface Transferability Matrix

The Subsurface Transferability Matrix organizes the assessed competency areas across four technical domain groupings: Geological Characterization, Petrophysical Evaluation, Dynamic Simulation, and Monitoring and Surveillance. Each competency area is assigned a transferability rating on a five-level scale: Direct Applicability without adaptation, Applicable with Moderate Adaptation, Applicable with Major Adaptation, Complementary but Indirect Applicability, and New Competency Required [9, 10]. The matrix ratings reflect comparison of technical objectives, physical conditions, fluid properties, regulatory requirements, and monitoring design principles between the petroleum and carbon storage contexts for each competency area.

The matrix is organized within a three-tier competency transfer model depicted in Figure 1: a Foundation Tier comprising competencies transferring directly from petroleum practice, an Adaptation Tier comprising competencies requiring targeted modification, and a New Competency Tier comprising capabilities that must be built outside the existing petroleum expertise base. This architecture provides a practical organizing principle for workforce transition program design, enabling organizations to sequence competency development investments according to the relative size of the capability gap in each domain [11, 12].

Niger Delta three-dimensional geological modeling competencies fall within the Foundation Tier, as the structural and stratigraphic interpretation workflows applied to growth-fault-bounded offshore fields [2] transfer essentially without modification to storage site structural and stratigraphic assessment. Analogue permeability estimation for Niger Delta green fields [3] provides a directly applicable methodology template for storage formation injectivity characterization under data-limited conditions, and regional formation water geochemistry [1] provides baseline information for geochemical compatibility assessment of formation fluids.

Table 1: Subsurface Transferability Matrix: Selected competency areas and transferability ratings

Domain	Competency Area	Transferability Level	Key Adaptation Required
Geological Characterization	3D Geological Modeling	Direct — Foundation Tier	Target properties differ: seal integrity emphasis added
Geological Characterization	Sequence Stratigraphy	Direct — Foundation Tier	Minimal: correlation framework identical
Geological Characterization	Caprock Integrity Assessment	Major Adaptation Required	Geochemical reaction + geomechanical modules required
Geological Characterization	Structural Interpretation	Direct — Foundation Tier	Trap geometry vs containment geometry emphasis shift
Petrophysical Evaluation	Well Log Analysis	Direct — Foundation Tier	Standard workflows directly applicable
Petrophysical Evaluation	Analogue Permeability Estimation [3]	Direct — Foundation Tier	Injectivity characterization application
Dynamic Simulation	Reservoir Simulation	Moderate Adaptation	CO2 EOS; geochemical reaction modules required
Dynamic Simulation	History Matching	Moderate Adaptation	Injection performance data replaces production data
Dynamic Simulation	Pressure Transient Analysis	Direct — Foundation Tier	Injectivity focus replaces productivity focus
Monitoring and Surveillance	Time-Lapse Seismic	Moderate Adaptation	CO2 acoustic response calibration required
Monitoring and Surveillance	Geochemical Monitoring	New Competency Required	CO2 detection in formation water; isotopic attribution
Monitoring and Surveillance	Surface Deformation Monitoring	New Competency Required	Long-term geodetic surveillance; regulatory reporting

SUBSURFACE TRANSFERABILITY MATRIX — THREE-TIER FRAMEWORK		
Layer	Component	Description
Direct Transfer (no or minor adapta)	3D Geological Modeling	structural and stratigraphic interpretation workflows
	Sequence Stratigraphy	correlation frameworks identical to petroleum exploration
	Well Log Analysis and Core Characterization	standard petrophysical evaluation directly applicable
	Analogue Permeability Estimation [3]	injectivity characterization direct application
	Pressure Transient Analysis	injectivity test interpretation using petroleum mathematical framework
Targeted Capability Extension Requi	Caprock Integrity Assessment	add geochemical reaction and geomechanical modules
	Reservoir Simulation	CO2 equation of state; mineral trapping reaction packages
	Time-Lapse Seismic Monitoring	CO2 acoustic response calibration; extended timescale
	History Matching	injection data replaces production data; long-term plume behavior
Must Be Built Outside Existing Expe	Commercial Framework Adaptation	carbon credit markets; liability management
	Geochemical Monitoring	formation water CO2 detection; isotopic source attribution
	Surface Deformation Monitoring	geodetic surveillance; regulatory closure protocols
	Injection-Induced Seismicity Management	fault activation monitoring; threshold management
	Long-Term Post-Injection Stewardship	100+ year model forecasting; regulatory site closure
	Storage Permitting and Regulatory Compliance	storage-specific environmental law

Fig 1: Subsurface Transferability Matrix: Three-Tier Competency Transfer Framework

4. Geological Characterization: Foundation Tier Assessment

Three-dimensional geological modeling, encompassing structural interpretation, stratigraphic correlation, facies architecture reconstruction, and geostatistical property simulation, represents the competency area with the highest direct transferability from petroleum to storage applications [13, 14]. Petroleum geological models target porosity, permeability, and hydrocarbon saturation as primary property distributions, while storage site models emphasize caprock seal integrity, formation water salinity, and mineralization potential in addition to the standard petrophysical parameters required for injectivity and capacity assessment.

Caprock integrity assessment represents the most significant geological characterization competency gap between petroleum and storage practice. While petroleum seal evaluation methods provide a foundational framework, the specific requirements of caprock integrity assessment for supercritical carbon dioxide storage include geochemical reaction modeling at the brine-carbon dioxide-caprock mineral interface, geomechanical analysis of fault reactivation potential under injection-induced pressure increase, and long-term creep modeling for argillaceous caprocks not typically required in standard petroleum trap evaluation workflows [15, 16].

The Niger Delta geological setting provides a particularly instructive regional context for caprock integrity assessment, with the growth-fault systems that bound petroleum reservoir compartments also creating the principal caprock integrity uncertainty for potential storage applications in the same stratigraphic column [2]. Formation water chemistry data from southwestern Nigerian investigations [1] provides the geochemical baseline information required for parameterizing brine-carbon dioxide-caprock mineral reaction models in this setting, illustrating the direct practical relevance of existing regional petroleum subsurface knowledge to storage site appraisal.

5. Petrophysical Evaluation and Dynamic Simulation

Wireline log analysis, core characterization, and fluid sampling methodologies transfer directly from petroleum to storage site evaluation with high applicability across all standard well evaluation activities, reflecting the fundamental similarity of measurement physics and interpretation objectives between the two application domains [17, 18]. The principal methodological extension required in the storage context is geochemical compatibility assessment, evaluating whether injected carbon dioxide will react adversely with formation minerals, formation water, or completion materials in ways that could impair injectivity or compromise containment [19, 20].

Multiphase flow simulation of carbon dioxide-brine systems draws directly on petroleum reservoir simulation methodologies, with adaptations required for the equation-of-state treatment of supercritical carbon dioxide, relative permeability and capillary pressure relationships appropriate for carbon dioxide-brine systems, and reactive transport mechanisms responsible for mineral trapping and dissolution trapping of injected carbon dioxide [21, 22]. Comparative evaluations of petroleum reservoir simulators adapted for carbon dioxide storage applications demonstrate that industry-standard simulation packages provide an adequate foundation for storage performance prediction

when supplemented with appropriate carbon dioxide fluid property packages and geochemical reaction modules [23, 24]. Pressure transient analysis and well test interpretation methods transfer directly from petroleum to storage applications for injectivity evaluation, as the mathematical framework governing pressure propagation in porous media is identical regardless of the fluid being injected [25, 26]. The primary application difference is the operational context: storage injectivity tests characterize formation transmissibility for long-duration injection planning rather than production rate optimization, and regulatory reporting requirements differ from those applicable to petroleum well tests.

6. Monitoring, Measurement, and Verification

Time-lapse seismic monitoring transfers to geological storage monitoring with moderate adaptation requirements concentrated in the specific acoustic impedance response of supercritical carbon dioxide and the extended monitoring timescales of post-injection site stewardship [27, 28]. The relatively high seismic impedance contrast between supercritical carbon dioxide and formation brine makes geological storage a favorable time-lapse seismic application domain that can detect plume extent and saturation changes at lower saturations than achievable for oil saturation monitoring in analogous reservoir settings [29, 30].

Geochemical monitoring programs, which sample formation water from monitoring wells to detect injected carbon dioxide through changes in dissolved gas content, isotopic composition, and mineralogy, represent a new capability requirement for most petroleum organizations entering the storage sector [31, 32]. The development of geochemical baseline characterization programs documenting pre-injection compositions of formation waters and groundwater aquifers to enable statistically robust detection of injection-related changes requires integration of petroleum geochemistry expertise with environmental monitoring methodology that constitutes a genuine competency gap for most petroleum organizations.

Long-term monitoring design, addressing the regulatory requirements for post-injection site stewardship that may extend over decades to centuries, represents the new competency domain with the largest departure from petroleum operational experience [33, 34]. IoT-enabled monitoring infrastructure, cloud-based data management, compliance-as-code governance for monitoring data streams, and predictive analytics frameworks from adjacent industrial monitoring programs provide enabling technology templates for the development of long-term monitoring programs that maintain cost efficiency while satisfying regulatory integrity demonstration requirements.

7. Commercial Framework and Implementation Pathways

The regulatory frameworks governing geological carbon dioxide storage differ substantially from petroleum regulations, with specific requirements for storage site permitting, injection monitoring, contingency planning, and post-injection site stewardship that have no direct equivalents in petroleum regulatory practice [35, 36]. The development of regulatory compliance capabilities requires petroleum organizations to build familiarity with storage-specific provisions of environmental regulations,

greenhouse gas accounting standards, and liability frameworks that govern long-term responsibility for stored carbon dioxide in each jurisdiction.

Commercial frameworks for geological storage, including emerging markets for carbon removal credits, government incentive programs for industrial carbon capture investment, and financial instruments for long-term storage liability management, differ fundamentally from the commodity-based commercial structures of petroleum production [37, 38]. Predictive financial analytics frameworks for complex project finance, risk-adjusted economic modeling under uncertain price scenarios, and financial planning models for long-duration infrastructure investments from adjacent capital project sectors provide useful templates for adapting commercial evaluation capabilities to the storage business model context.

Implementation pathway design for petroleum organizations entering the geological storage sector should be sequenced to leverage the Foundation Tier competencies that are immediately deployable in storage site assessment activities, generating early-stage technical value while the more time-consuming Adaptation Tier and New Competency Tier development programs are underway [39, 40]. Early participation in storage site appraisal projects as a technical partner to more experienced storage operators provides the practical learning environment required for efficient new competency development that supplements but does not replace formal training programs.

Table 2: Key adaptations required when applying petroleum simulation methods to CO₂ storage

Simulation Activity	Petroleum Standard Practice	Required Adaptation for Storage	Adaptation Difficulty
Fluid PVT Modeling	Hydrocarbon EOS (Peng-Robinson)	CO ₂ -brine EOS; supercritical phase behavior	Moderate
Relative Permeability	Oil-water-gas kr curves	CO ₂ -brine kr; trapping hysteresis critical	Moderate
Capillary Pressure	Oil-water Pc for drainage/imbibition	CO ₂ -brine Pc; entry pressure for seal evaluation	Moderate
Geochemical Reactions	Not typically included in reservoir simulation	Mineral dissolution/precipitation; trapping mechanisms	High
Geomechanics Coupling	Reservoir compaction (optional)	Fault reactivation; caprock integrity (mandatory)	High
Long-term Forecasting	Production lifecycle (20-30 yr)	Post-injection monitoring (100-1000 yr horizon)	High

8. Organizational Enablers

The organizational enablement of the technical advances reviewed in this paper requires leadership commitment to quality standards that resist schedule and cost pressures, cross-disciplinary team integration that genuinely connects subsurface, engineering, and commercial expertise during analytical and decision-making activities, and sustained investment in data governance infrastructure that maintains the quality and accessibility of the subsurface knowledge base across organizational transitions and asset ownership changes [56, 57]. These organizational prerequisites represent the foundational conditions without which even the most

algorithmically sophisticated methodological advances fail to deliver their potential commercial value in practice. Supply chain resilience frameworks, occupational safety management systems, and compliance governance programs from adjacent operational sectors provide structural analogues for the program governance infrastructure required to sustain technical quality in petroleum geological carbon dioxide storage and petroleum subsurface characterization programs [58, 59].

Key performance indicator frameworks adapted from organizational management research provide monitoring mechanisms for tracking the implementation progress of technical quality improvement programs across project cycles, enabling early identification of capability gaps or process compliance deficiencies before they affect commercial decision quality [60, 61]. Digital governance infrastructure including IoT-enabled monitoring platforms, cloud-based data management systems, AI governance frameworks for algorithmic decision support, and blockchain-enabled audit trail management provide the enabling technology layer for sustained technical quality programs that maintain calibration and compliance visibility across large and complex asset portfolios [62, 63, 64]. Safety management systems and environmental compliance frameworks from petroleum operations provide direct organizational governance templates that many petroleum technical teams can adapt from their existing operational governance programs rather than building entirely new structures.

The development of standardized technical assessment instruments, including the framework proposed in this paper, plays an important organizational role by providing a shared vocabulary and measurement system for technical quality that enables comparison across project teams, asset classes, and organizational units in ways that informal quality judgments cannot support [65, 66]. Collaborative industry initiatives that share calibration data, benchmark test cases, and framework validation evidence across organizational boundaries would substantially accelerate the adoption of improved practice standards across the sector, drawing on models established in adjacent industries where pre-competitive technical standardization has demonstrably improved sector-wide performance without compromising competitive differentiation at the commercial level [67, 68].

9. Discussion

The synthesis presented in this paper reveals several consistent patterns in the relationship between methodological quality and commercial performance outcomes across the geological carbon dioxide storage and petroleum subsurface characterization literature. Studies documenting the most reliable technical outputs and the strongest alignment between pre-development estimates and post-development outcomes consistently exhibit three shared attributes: rigorous probabilistic uncertainty quantification applied across all primary input parameters, genuine cross-disciplinary integration of geological, engineering, and commercial expertise during framework application, and organizational governance programs that sustain analytical quality through the pressures of schedule and cost that routinely compromise rigor in practice [69, 70]. These attributes are as much organizational as technical, confirming that the highest-impact investments for improving the commercial value of geological carbon

dioxide storage and petroleum subsurface characterization programs are often in governance and capability development rather than in algorithmic advancement.

The Niger Delta provincial evidence reviewed throughout this paper demonstrates both the technical challenges and the commercial opportunities associated with mature methodology application in complex West African clastic settings. The growth-fault-bounded compartmentalization, rapid lateral facies variability, and active aquifer systems characteristic of Niger Delta petroleum accumulations create characterization challenges that place demanding requirements on nearly every dimension of the proposed framework, but also create disproportionately large commercial rewards for operators who achieve high-quality framework compliance because the complexity of these systems creates significant informational advantages for those who characterize them rigorously [71, 72, 73]. The analogue-based permeability estimation methodology [3] and the three-dimensional static modeling benchmarks [2] documented for this province represent practically accessible quality improvement pathways that do not require frontier technology investments.

Several dimensions of current practice remain below the standard that the proposed framework identifies as best practice, and the commercial cost of these gaps is significant across the global portfolio of petroleum assets applying the relevant methods. Legacy data integration deficiencies, organizational knowledge retention gaps, and the inconsistent application of probabilistic uncertainty frameworks to economic evaluation represent the most frequently documented below-threshold dimensions, each with root causes traceable to organizational incentive structures and workflow design choices that are amenable to systematic improvement through the governance interventions described in Section 8 [74, 75, 76]. Future research priorities include the development of quantitative empirical relationships between practice quality indicator scores and commercial performance outcomes, the standardization of quality assessment protocols across organizational contexts, and the investigation of the organizational factors that most strongly predict successful implementation of technical quality improvement programs across diverse corporate environments [77, 78].

The synthesis of technical advances reviewed in this paper identifies consistent patterns between methodological quality and commercial performance across the published evidence base. Research studies documenting the most reliable technical outputs and the strongest pre-development-to-post-development alignment consistently exhibit three shared attributes: rigorous probabilistic uncertainty quantification applied across all primary input parameters, genuine cross-disciplinary integration of geological, engineering, and commercial expertise, and organizational governance programs that sustain analytical quality through the schedule and cost pressures that routinely compromise rigor in operational settings [79, 80]. The established reservoir engineering frameworks of Dake [5], Ahmed [6], and Oliver *et al.* [8] provide the foundational theoretical underpinning for all the methodological advances reviewed here, and remain the essential starting point for any practitioner seeking to understand the physical principles governing the quantitative methods discussed throughout.

The fundamental geostatistical modeling frameworks of

Caers [6], Pyrcz and Deutsch [9], and Deutsch and Journel [12] continue to underpin current ensemble-based uncertainty quantification practice, even as machine learning approaches from LeCun *et al.* [13] and Goodfellow *et al.* [15] are progressively integrated as complementary components within hybrid physics-machine learning architectures [81, 82]. The ensemble Kalman filter formulation of Evensen [7] and its iterative variants developed by Emerick and Reynolds [8] represent the current methodological standard for model calibration against production history. Doust and Omatsola [10] provide the essential Niger Delta geological framework within which the regional petroleum engineering advances reviewed in this paper are situated [83, 84].

The limitations inherent in the narrative review methodology adopted in this paper include the potential for selection bias in literature identification, the inability to statistically aggregate findings across heterogeneous study designs, and the dependence on published evidence that underrepresents proprietary technical advances not disclosed in the open literature [85, 86]. Readers in geological contexts other than Niger Delta clastic systems, including carbonate reservoirs, tight gas formations, or deep subsalt environments, should adapt framework prescriptions with consideration of the specific geological and operational conditions distinguishing their context from the primary calibration base. Collaborative industry data sharing initiatives would provide the empirical calibration datasets enabling statistical validation of framework prescriptions currently not achievable from the available public literature [87, 88].

Future research priorities identified from this synthesis include the development of quantitative empirical relationships between practice quality indicator scores and commercial performance outcomes, the standardization of framework assessment protocols across organizational contexts to enable meaningful industry-wide benchmarking, and the systematic investigation of organizational factors most strongly predicting successful implementation of technical quality improvement programs across diverse corporate environments [89, 90]. The cross-domain applicability of petroleum subsurface characterization capabilities to geological carbon dioxide storage, building on the foundational storage science of Bachu [18] and Michael *et al.* [19], represents a research frontier with increasing strategic importance as the petroleum industry evaluates its role in broader energy transition programs. The Ringrose and Meckel [45] assessment of global CO₂ storage resources and the time-lapse seismic monitoring methodology of Lumley [20] provide the scientific basis for applying petroleum monitoring expertise to storage site performance verification.

The organizational dimensions of technical quality in petroleum subsurface programs have received increasing attention in the published literature as operators recognize that the gap between leading and median practice is rarely attributable to differences in methodological knowledge or computational capability, which are broadly accessible through technical publications, commercial software, and professional development programs. Rather, the gap is consistently attributable to organizational factors including leadership prioritization of schedule over analytical rigor, inadequate investment in legacy data management infrastructure, insufficient cross-disciplinary integration in project teams, and the loss of institutional knowledge

through workforce transitions that leave model files intact but organizational understanding depleted^[91, 92]. Addressing these organizational root causes requires the governance framework investments described throughout this review to be treated as primary program elements rather than supporting activities secondary to the technical modeling work, a recognition that is reflected in the framework dimension structure proposed here.

The framework proposed in this review has been designed to be applicable across the full spectrum of organizational sizes and resource levels represented in the global petroleum industry, from large integrated operators with dedicated specialist technical teams to smaller independent producers with generalist subsurface staff who must apply the same fundamental uncertainty management principles with more constrained resources. For smaller organizations, the framework dimensions most likely to deliver disproportionate commercial value per unit of investment are those addressing fundamental data quality and probabilistic forecast completeness, which have the highest leverage on capital allocation decision quality regardless of organizational scale^[93, 94]. For larger organizations with more mature technical programs, the digital integration and organizational knowledge retention dimensions often represent the highest remaining improvement potential because these dimensions require sustained investment in infrastructure and documentation governance that is frequently deprioritized against technically more visible activities during periods of organizational pressure.

The review also highlights the importance of maintaining a balanced perspective on the role of advanced analytical methods relative to the quality of their input data and the organizational governance that determines whether their outputs are used to inform decisions. The most sophisticated ensemble-based uncertainty quantification method, drawing on the foundational contributions of Evensen^[7], Emerick and Reynolds^[8], Oliver *et al.*^[8], and Gu and Oliver^[23], cannot generate reliable probabilistic forecasts from a petrophysical database that has not been properly normalized across vintage log generations, nor can it compensate for the loss of geological reasoning embedded in a model when the original interpreters leave the organization without documenting their conceptual framework. These organizational prerequisites for technical quality, captured in the data integration and knowledge retention dimensions of the proposed framework, represent the foundational investment upon which all methodological advances must build to deliver their full commercial potential^[95, 96].

The strategic importance of the Subsurface Transferability Matrix for petroleum industry planning extends beyond individual project decisions to encompass the organizational investment portfolio decisions that will determine which petroleum companies are positioned to participate in geological storage markets as they mature through the 2020s and 2030s. Companies that systematically assess their competency positions against the matrix and invest in identified gaps through the implementation pathways described in Section 7 will develop the technical credibility and project delivery capability required to compete for storage project leadership roles that are projected to become significant revenue-generating opportunities within the decade^[41, 42].

10. Conclusion

The Subsurface Transferability Matrix proposed in this review provides petroleum organizations with a structured, evidence-based instrument for assessing and planning the workforce adaptation required to deploy existing subsurface characterization expertise in geological carbon dioxide storage applications. Matrix analysis confirms that the majority of petroleum subsurface characterization capabilities transfer to the storage domain with limited to moderate adaptation, representing a substantial competitive advantage for petroleum organizations entering the storage sector. The three highest-priority new competency development areas, caprock geochemical response modeling, injection-induced geomechanics, and long-term post-injection monitoring design, define a focused capability development agenda achievable within the career timescales of existing petroleum technical workforces.

Niger Delta regional evidence confirms that three-dimensional geological modeling^[2] and petrophysical characterization capabilities^[3] developed in complex West African clastic petroleum settings are directly transferable to storage site assessment requirements in comparable basin environments. The organizational implementation roadmap, sequenced to leverage Foundation Tier competencies for early value capture while building Adaptation and New Competency Tier capabilities systematically, provides a practical program design template for petroleum organizations committing to geological storage market entry.

This review provides accessible synthesis of methodological advances and practical guidance for operational practitioners. The framework, tables, and framework diagram are designed to support rapid orientation to the key dimensions and available methods. Readers requiring greater methodological depth in specific domains are directed to the primary literature cited throughout this review.

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