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Geophysical Detection and Monitoring of CO_2 Trapping Mechanisms in Geological Reservoirs

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1. Introduction

1.1 Geological CO_2 Storage and Long-Term Containment

Anthropogenic carbon dioxide (CO_2) emissions are a major driver of global climate change, resulting in a growing demand for technologies to abate emissions from power generation and carbon-intensive industrial processes. Therefore, carbon capture and storage (CCS) has become a key mitigation option especially for those industries that still have technical or economic constraints to full de-carbonization. The last step of the CCS chain is geological storage of CO_2, which involves injecting the captured CO_2 into suitable subsurface formations where it can be isolated from the atmosphere for sufficiently long time scales. The main geological targets for CO_2 storage are deep saline aquifers and depleted oil and gas reservoirs. Saline formations are attractive because of their widespread distribution and potentially large storage capacity. Depleted hydrocarbon reservoirs have a number of advantages related to their prior exploration and production history. Seismic surveys, well logs, core measurements, pressure data, production histories and existing reservoir models may contain a wealth of information that can be used to evaluate reservoir architecture, storage capacity, injectivity and seal integrity. Many hydrocarbon reservoirs have also been shown to retain fluids over geological time scales, suggesting that they could be used to store CO_2. At typical geological storage depths (generally > ~ 800 m depending on local pressure and temperature conditions), CO_2 is typically in the form of a dense or supercritical fluid. The increased density under these conditions means that large quantities of CO_2 can be stored in reservoir pore space. But, in general, CO_2 is less dense and less viscous than formation brine, leading to a complex multiphase flow system after injection. Injection-induced pressure gradients initially dominate fluid flow but buoyancy, capillary forces, reservoir heterogeneity, wettability, and fluid-rock interactions progressively influence the migration and redistribution of plumes. The injected CO_2 does not therefore stay concentrated around the injection well. It can migrate laterally via high permeability pathways and vertically under buoyancy, accumulate under low permeability geological barriers, become disconnected and immobilized in pore space, dissolve into formation water and ultimately participate in geochemical reactions with reservoir minerals. Consequently, the spatial distribution and physical state of the stored CO_2 change during both the injection and post-injection periods. This evolution is largely driven by reservoir heterogeneity. CO 2 distributions can be highly nonuniform due to variations in permeability, porosity, pore-throat size, capillary entry pressure, facies architecture, fractures, and mineralogy. Preferential migration in permeable layers can be associated with local accumulation below capillary barriers and small-scale heterogeneity can determine whether CO_2 remains connected or becomes immobilized during subsequent brine imbibition. These processes provide an important connection between petroleum reservoir physics and geophysical monitoring as the resulting fluid distribution affects the effective physical properties measured by geophysical techniques.

Hence, the long-term storage security is not only dependent on the capacity of the formation to receive CO 2 but also on the processes that progressively restrict its mobility. Storage reliability assessments require understanding of how the CO_2 migrates, how much remains in the target storage complex, how its

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saturation changes, and how it evolves from a mobile free phase to more effectively trapped states. One of the basic technical requirements of geological CO 2 storage is to monitor such changes.

1.2 CO_2 Trapping Mechanisms in Geological Reservoirs

The long-term storage of injected CO_2 is controlled by a variety of physical and geochemical processes operating at different spatial and temporal scales. There are generally considered to be four particularly important mechanisms: structural and stratigraphic trapping, residual or capillary trapping, solubility trapping and mineral trapping. These mechanisms are not independent and their relative contributions change over the lifetime of a storage project. The buoyant free-phase CO_2 migrates upward and is trapped under low-permeability caprock or in geological closures, which are structural and stratigraphic traps. Vertical or lateral migration may be limited by anticlines, fault-bounded structures, stratigraphic pinch-outs or internal low-permeability layers. The importance of this mechanism is particularly high in the injection and early post-injection periods, when a substantial fraction of the injected CO 2 may be in a connected free phase. Time-lapse seismic observations at field scale have shown that thin intrareservoir barriers can have a strong influence on plume geometry and lead to vertically separated CO_2 accumulations [1,2]. Another important mechanism to reduce the mobility of CO_2 is residual or capillary trapping. The non-wetting CO_2 phase displaces formation brine during CO_2 injection in a drainage process. The previously connected CO_2 phase may split into disconnected bubbles and ganglia when brine later reenters CO_2-occupied pore space during imbibition. The isolated clusters are trapped by capillary forces and cannot readily contribute to further buoyancy-driven migration. Therefore, residual trapping is crucial for improving the security of storage relatively soon after injection. Residual trapping magnitude and distribution depend on pore-throat geometry, wettability, interfacial tension, capillary pressure, saturation history, drainage-imbibition hysteresis and reservoir heterogeneity. Therefore, residual trapping is inherently tied to pore scale fluid displacement. However, geophysical measurements typically probe volumes many orders of magnitude larger than single pores. Linking pore-scale immobilization to reservoir-scale geophysical observations is a major multiscale problem. Solubility trapping: Free-phase CO 2 is dissolved into the formation water. Dissolution removes the buoyancy of a separate CO_2 phase and thus reduces the likelihood of upward migration. Dissolution rate and amount are dependent on pressure, temperature, brine salinity, CO_2-brine interfacial area and hydrodynamic mixing. The dissolution of CO 2 can also increase the density of the brine, which can lead to gravitational instabilities that can enhance convective mixing and further enhance the dissolution. Mineral trapping is a longer term geochemical process in which dissolved carbon is involved in reactions with formation minerals and can eventually be incorporated into stable solid phases. Rate and extent of mineralization is strongly dependent on mineral composition, reactive surface area, temperature, fluid chemistry and reaction kinetics. Mineral trapping can provide very stable carbon immobilization, but the importance and timescale vary widely across geological formations. Therefore, the evolution of geological storage can be thought of as a transition from relatively mobile to increasingly immobilized forms of CO_2:

Free-phase migration → structural containment → capillary immobilization → dissolution → mineralization.

This sequence is necessarily simplified, because a number of mechanisms can be operating simultaneously. For example, part of a plume may be structurally trapped, part may be residually immobilized, and part may dissolve into brine. The relative proportions can also vary considerably with time.

The fundamental problem of monitoring is the constantly changing nature of trapping. Finding the CO_2 plume does not tell us how securely the CO_2 is trapped. A reservoir region with free-phase mobile CO_2 and another with disconnected residual CO_2 may

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have similar average saturation but very different implications for long-term migration risk. Similarly, dissolved or mineralized CO_2 may induce much weaker geophysical contrasts than free-phase CO_2. A monitoring framework aimed at assessing long-term storage security must therefore move beyond plume detection to characterization of CO_2 physical state and trapping mechanism.

1.3 Geophysical basis for detection and monitoring of CO_2

Monitoring, measurement and verification are key elements of geological storage of CO_2. Monitoring is necessary to confirm that injection is taking place as anticipated, to delineate the migration of the injected plume, to assess the efficacy of the storage, to identify unforeseen migration routes, to demonstrate containment, and to provide proof of the long-term security of the storage. Wells provide direct measurements of reservoir conditions, but their spatial coverage is inherently limited. Geophysical methods have the important advantage that they can provide information over much larger subsurface volumes and can be repeated during and after the injection. The physical basis of geophysical monitoring of CO 2 in reservoirs is the alteration of reservoir properties as a consequence of fluid substitution and pressure change. The substitution of brine by CO 2 leads to a change in the effective density, compressibility, elastic moduli, acoustic impedance and electrical conductivity of the rock-fluid system. The pressure changes induced by injection may also affect the stress state and elastic response of the reservoir. Seismic, electrical, electromagnetic, gravity and borehole observations can detect such changes. Time-lapse seismic monitoring is one of the most established approaches to monitor geological CO_2 storage. Brine replacement with compressible CO_2 has a considerable effect on P-wave velocity and acoustic impedance, which leads to measurable changes in reflection amplitude and travel time. The comparison of baseline and repeat seismic surveys enables imaging of the spatial evolution of the plume. One of the most prominent examples of this approach is the Sleipner storage project in the North Sea where repeated seismic datasets have demonstrated progressive CO_2 accumulation beneath several intra-reservoir barriers [1,2].

Quantitative interpretation is more than just plume visualization. Rock-physics models can relate changes in seismic properties to CO_2 saturation, and thus allow seismic inversion and tomography to estimate fluid distributions. Quantitative analysis of Sleipner data has shown that seismic observations, together with appropriate rock-physics assumptions, can be used to estimate CO_2 saturation [3]. However, the relationship between saturation and seismic response is not unique. The measured response may be affected by pressure, temperature, pore structure, fluid distribution and patchy vs. homogeneous saturation.

Electrical methods provide a complementary sensitivity to CO 2 substitution. Formation brine is usually electrically conductive due to dissolved ions, whereas CO_2 is comparatively resistive. CO_2 replacement of conductive brine can increase bulk formation resistivity. Electrical resistivity tomography (ERT) has been successfully applied to CO 2 monitoring in crosshole and surface downhole configurations, e.g. at the Ketzin pilot storage site [6–9]. Time-lapse ERT can deliver complementary information to seismic observations on the migration of plumes and changes in saturation. Gravity measurements are sensitive to changes in the subsurface density and mass distribution. The CO_2 is less dense than formation brine with typical reservoir conditions so that displacement of brine by CO_2 can produce small but measurable gravity changes. Sleipner gravity observations of the seafloor have been used to constrain the CO_2 density and plume evolution using seismic data [4,5]. Gravity measurements usually have lower spatial resolution than seismic imaging but can provide useful independent constraints on subsurface mass changes. Additional monitoring capabilities are provided by borehole techniques. Vertical seismic profiling (VSP) and crosswell seismic tomography provide higher resolution around monitoring wells than conventional surface seismic surveys. Their utility in characterizing changes associated with

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CO_2 injection and relating seismic velocity changes to saturation has been demonstrated at Frio and Cranfield [10,11]. Most recently, distributed acoustic sensing (DAS) has allowed permanent or semi-permanent seismic monitoring using fiber-optic cables. DAS-based systems have the potential to be used for repeated reservoir monitoring, as demonstrated by applications at the CO_2CRC Otway project [12–14].
Sensitivity of these methods is very different. Seismic methods are sensitive to changes in elastic properties, ERT and electromagnetic methods to electrical properties and gravity to density and mass redistribution. Their distinct sensitivities provide an important argument for the multiphysics monitoring. A change that is ambiguous in one data set may be better constrained by the joint interpretation of several independent physical measurements.

1.4 From CO_2 Plume Detection to the Identification of the Trapping State

While there have been significant advances in the geophysical monitoring of CO_2, an important difference remains between the detection of CO_2 and the identification of the mechanism by which it is immobilized. This distinction is important when assessing the security of long-term geological storage.
Most of the well established geophysical techniques are particularly sensitive to free-phase CO_2, since an exchange of brine by CO_2 can produce large contrasts in elastic and electrical properties. Thus, given favorable geological and acquisition conditions, the location and approximate geometry of a free-phase CO_2 plume can be determined. But a geophysical anomaly detecting CO_2 presence does not necessarily establish whether the detected CO_2 is still mobile or has become safely immobilized. This limitation is illustrated by residual trapping. During brine imbibition, when CO_2 becomes disconnected into isolated ganglia, the mobility of CO_2 can decrease drastically yet the total CO_2 saturation in the measurement volume is still significant. A typical seismic measurement is therefore sensitive to the effective elastic properties of this mixed fluid-rock system, rather than to phase connectivity directly. Therefore, the identification of mobile connected CO 2 from immobile residual CO_2 needs to be sensitive to pore-scale fluid configuration as well as bulk saturation. Fluid distribution is important, especially for rock-physics interpretation. Different seismic velocities, attenuation and frequency dependent responses can be obtained from homogeneous and patchy saturation even if the average CO_2 saturation is similar. Capillary heterogeneity may also lead to complex saturation patterns that cannot be properly described by simple uniform fluid-substitution models. These effects create uncertainty in inferring trapping state from seismic measurements at the reservoir scale.
Another major problem is the pressure–saturation ambiguity. An injection changes both fluid saturation and reservoir pressure, and both of these variables can affect seismic velocity and impedance. In addition, the pressure perturbations might be able to propagate outside the free-phase CO_2 region. Hence, a time-lapse seismic anomaly may be caused by a combination of saturation change, pressure change, stress effects, and geologic heterogeneity. A quantitative assessment of the trapping requires separating these contributions as reliable as possible.
Solubility trapping is even more difficult to geophysically identify. Dissolved CO_2 usually produces smaller elastic and electrical contrasts than free-phase CO_2. Thus, a decrease in a seismic or resistivity anomaly during post-injection monitoring cannot be automatically interpreted as evidence for dissolution. Plume spreading, pressure equilibration, saturation redistribution or movement below the resolution limit of the survey could generate similar observations. Thus, quantification of solubility trapping will likely require integration of geophysical data with geochemical measurements and reservoir simulation. Mineral trapping is the most difficult to verify geophysically directly. Density, porosity, permeability, elastic moduli, and electrical properties may be altered by mineral dissolution and precipitation. But these changes may be slow and small compared to natural geological variability. Compaction, cementation, pressure evolution or other diagenetic processes can also cause similar property

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changes. Therefore, geophysical observations alone may not be enough to uniquely attribute a measured change to mineralized carbon. These challenges expose a fundamental non-uniqueness problem. Geophysical instruments measure physical properties, not trapping mechanisms. The interpretation chain can be written as:

Trapping process -> fluid/mineral redistribution -> change in physical properties -> geophysical response -> inversion -> inferred reservoir state

Uncertainty can creep in anywhere along this chain. Thus, rock physics provides the essential bridge between processes occurring in the reservoir and the measured geophysical signals. To move from qualitative plume imaging to quantitative identification of trapping states, monitoring must better understand fluid substitution, patchy saturation, capillary effects, pressure dependence and pore-scale fluid configuration. Field-scale projects show the strengths and weaknesses of existing methods. Time-lapse seismic and gravity monitoring has been shown to be effective for plume characterization at Sleipner [1–5]. Integrated seismic and electrical monitoring has provided extensive evidence by Ketzin [6–9]. Frio and Cranfield have offered high-resolution borehole data [10,11] and Otway has advanced VSP and fibre-optic monitoring techniques [12–14]. Taken together, these projects show that injected CO_2 can be successfully monitored, but also that there is no single geophysical method that can uniquely characterize saturation, connectivity, mobility, and trapping mechanism under all reservoir conditions. So, integrated monitoring is becoming more and more important. Seismic and ERT or electromagnetic observations jointly provide complementary sensitivity to elastic and electrical properties. Gravity measurements can constrain changes in mass and density. Well logs and pressure observations provide local calibration. Integration with reservoir-flow simulations allows testing the physical consistency of observed plume evolution to predicted migration and trapping. Joint inversion and history matching can further reduce uncertainty by constraining multiple reservoir parameters simultaneously. New technologies could further reinforce this approach. Full-waveform inversion has the potential to enhance quantitative seismic imaging, and DAS could facilitate frequent and inexpensive monitoring with permanently installed fiber-optic infrastructure. Digital rock physics provides a link between pore-scale fluid configurations and effective geophysical properties, and machine-learning approaches can facilitate the extraction of complex relationships from large time-lapse data sets. But in the end, these technologies have to deal with the underlying physical non-uniqueness, not just with bigger data volumes or computational complexity.

1.5 Scope, Objectives and Structure of the Review

There is an extensive body of literature on geophysical monitoring of geological CO_2 storage including time-lapse seismic imaging, electrical monitoring, gravity measurements, borehole observations, leakage detection, and monitoring, verification and accounting frameworks. Much of the previous work has rightly been focused on detection of injected CO_2 and plume migration. However, the security of long-term storage is increasingly dependent on understanding the transition of CO_2 from a mobile phase toward structurally contained, residually immobilized, dissolved and finally mineralized states. Thus, the main goal of this review is to critically assess the capability of the current geophysical methods to detect, quantify, monitor and distinguish the main CO 2 trapping mechanisms in geological reservoirs. The review takes a process-based perspective, interpreting geophysical observations in terms of the physical and geochemical processes controlling CO_2 retention, rather than considering individual geophysical techniques as stand-alone monitoring technologies. Special emphasis is given to structural and stratigraphic trapping, residual/capillary trapping, solubility trapping and mineral trapping. We investigate their expected impacts on the elastic, electrical and density properties of the reservoir to determine which trapping processes produce geophysical signatures that are detectable, and which are difficult to identify

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directly. The review also assesses the main geophysical methods for geological storage monitoring, such as time-lapse surface seismic, VSP, crosswell seismic tomography, DAS, ERT, electromagnetic methods and gravity monitoring. Rock-physics relationships are defined as the quantitative link between the measured geophysical properties and the CO2 saturation, distribution, and physical state. The paper brings together evidence from the major field scale storage projects, notably Sleipner, Ketzin, Frio, Cranfield and Otway, to assess how well monitoring techniques perform under realistic geological conditions. We focus on whether field observations can distinguish between mobile free-phase CO_2 and residually trapped CO_2 and whether geophysical measurements can tightly constrain dissolution and mineralization. The review also considers integrated and multiphysics monitoring as a means to reduce interpretation uncertainty. Integration of seismic, electrical, gravity, well, geochemical, and reservoir-modeling information can place stronger constraints on the state of CO_2 than any one data set alone. Emerging developments in full-waveform inversion, DAS, digital rock physics, joint inversion, machine learning and physics-informed modeling are also considered in relation to future quantitative monitoring requirements.

2. CO_2 Trapping Mechanisms and Their Geophysical Signatures

The security of geological storage is governed by the progressive redistribution of injected CO_2 among a number of physical and geochemical states. Upon injection, CO_2 can exist as a mobile free phase, in a trapped state beneath geological barriers separated by capillary processes, dissolved into formation water, or eventually be involved in reactions that mineralize carbon into stable minerals. In general, these processes are classified into structural and stratigraphic trapping, residual or capillary trapping, solubility trapping and mineral trapping. This classification is useful from a conceptual point of view. The mechanisms are not independent but concurrent and their relative importance varies during the injection and post injection periods. From the geophysical point of view the distinction among these mechanisms is especially important. Geophysical instruments do not directly measure trapping mechanisms. They measure changes in properties such as seismic velocity, impedance, attenuation, density, electrical resistivity or electromagnetic response. Such a trapping mechanism to be detectable only if it alters one or more of these properties sufficiently to generate a resolvable signal. The detection of CO_2 is therefore fundamentally different from the determination of the trapping state. The literature reviewed here suggests a clear hierarchy of detectability. Typically, the strongest and most readily observable geophysical signature is produced by free-phase CO_2 that accumulates below structural or stratigraphic traps [1–8]. Residual CO_2 that can be detected geophysically may be present as a separate fluid phase, but it is far more difficult to distinguish disconnected residual CO_2 from connected mobile CO_2 [14,16,21–24,34]. Dissolution trapping gives weaker and less distinctive geophysical contrasts, and is usually inferred from time-dependent observations, mass balance or multiphysics interpretation [4,8,19,25–28,35]. The safest, but currently least directly observable mechanism with field-scale geophysical methods is mineral trapping [29–33].

2.1 Physical Basis and time evolution of CO_2 trapping

Injected CO 2 usually enters a reservoir as a dense or supercritical non-wetting phase. Its governing is the competition between viscous forces induced by injection, gravitational forces induced by the density contrast between CO_2 and formation water and capillary forces associated with fluid-fluid and fluid-rock interfaces. All three effects are altered by the geological heterogeneity resulting in the spatial variation of permeability, pore-throat size, capillary entry pressure, and flow connectivity. During injection, pressure gradients initially push CO_2 away from the injection well. In general, supercritical CO 2 is less dense than brine, so buoyancy promotes upward migration of the plume away from the high-pressure injection zone. Preferential flow develops

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through high permeability strata. Low permeability or fine-grained units can retard vertical migration through permeability and capillary-barrier effects. When the plume encounters a geological closure or impermeable seal, some of the free phase CO_2 becomes structurally or stratigraphically trapped. At the same time, brine redistribution behind the advancing plume can initiate imbibition. The non-wetting phase CO_2 then becomes disconnected, as snap-off and similar displacement mechanisms isolate CO_2 into isolated clusters, resulting in residual trapping [21–24].
The remaining free phase CO 2 continues to interact with the surrounding brine. Molecular diffusion is the transfer mechanism of the CO_2 across the phase interface but dissolution can be greatly enhanced by gravitational convection when the CO_2 enriched brine becomes denser than the underlying unsaturated brine [25,35]. Such mixing can be enhanced or suppressed by geological heterogeneity depending on permeability architecture and the relation between buoyant flow and stratification [26–28].
Dissolved CO_2 modifies the aqueous chemistry and can react with formation minerals. Acidification initially promotes dissolution of susceptible minerals, releasing divalent cations such as Ca^{2+}, Mg^{2+}, and Fe^{2+}. Under favorable conditions these cations subsequently react with carbonate species and precipitate as carbonate minerals, producing mineral trapping [29–33].
The commonly used conceptual progression,
mobile CO_2 → structurally contained CO_2 → residually trapped CO_2 → dissolved CO_2 → mineralized carbon,
therefore represents a change in both mobility and physical state. Storage security generally increases along this progression, but geophysical detectability tends to decrease. This inverse relationship is central to the monitoring problem addressed in this review.

2.2 Structural and Stratigraphic Trapping

Structural and stratigraphic trapping happens when buoyant free phase CO_2 is trapped beneath a sealing formation or geological structure which stops further migration. Anticlines, stratigraphic pinch-outs, fault-bounded compartments, low-permeability interbeds and capillary barriers form the basis of this mechanism. This trapping mode is often associated with a discrete free CO 2 phase replacing brine, resulting in some of the strongest contrasts encountered in geophysical monitoring. Changes in compressibility and bulk density modify seismic velocity and acoustic impedance, and replacement of conductive brine by electrically resistive CO_2 modifies the bulk electrical properties.

2.2.1 Sleipner: direct evidence for stratigraphically-controlled plume development

One of the first and most influential demonstrations of time-lapse seismic monitoring of injected CO 2 was by Arts et al. [1]. At Sleipner the seismic surveys have repeatedly identified several high amplitude reflections in the Utsira Sand, not a single uniform plume. These reflections are interpreted as discrete accumulations of free phase CO_2 trapped beneath thin mudstone layers within the reservoir. This result is not only important for simple CO_2 detection. It revealed that the internal stratigraphic architecture can control the development of the plume, even if the storage unit is thick and apparently homogeneous. Thin barriers may be inconsequential to traditional reservoir descriptions but they can have a profound effect on vertical CO 2 migration and result in a tiered system of accumulations. Later, Chadwick et al. [2] applied a quantitative analysis of the time-lapse observations and showed that the plume dimensions and temporal evolution could be constrained from seismic data. The study also showed, however, how difficult it is to translate seismic amplitude directly into unique estimates of CO_2 saturation. Thin-bed tuning, unresolved small scale fluid distribution, seismic velocity uncertainty and rock-physics assumptions all influence the interpretation. This problem was solved by Yan et al. [3] using seismic tomography and rock-physics inversion. The resulting work showed that from seismic velocity changes quantitative estimations of CO_2 saturation can be obtained, but the saturation obtained is still model dependent. Specifically, assumptions on fluid distribution and patchiness influence the correlation

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between observed velocity and saturation. The Sleipner studies thus demonstrate three sequential monitoring levels: plume detection [1], quantitative plume characterization [2] and saturation inversion [3]. Structural and stratigraphic trapping can be confidently identified as the geometry of the accumulation can be related to known geological barriers. However, the exact amount and physical configuration of the trapped CO_2 is more uncertain.

2.2.2 Structural accumulation of gravity constraints

Repeated gravity measurements provide a complementary constraint on the density of stored CO2 at Sleipner [4]. Alnes et al. [4] showed that Unlike seismic which is sensitive to elastic contrasts, gravity is sensitive to changes in subsurface mass distribution. Zumberge et al. [5] demonstrated that high-precision seafloor gravity and pressure measurements can detect temporal changes small enough to be useful for reservoir monitoring. Gravity does not have the spatial resolution of seismic imaging but can constrain bulk density and stored mass. Joint interpretation of seismic plume geometry with gravity-derived density removes some of the ambiguity inherent in seismic-only interpretations.

2.2.3 Ketzin and multi-method confirmation of containment

Bergmann et al. [6] reviewed the geophysical monitoring at Ketzin and demonstrated that seismic, vertical seismic profiling, electrical methods and inversion can be combined to characterize CO 2 migration. One of the main lessons from Ketzin was that the different methods measure different physical consequences of the same fluid-displacement process. Quantitative information about saturation changes could be obtained from time-lapse AVA analysis, as demonstrated by McDonald et al. [6]. AVO behavior is a function of the elastic contrasts across the reservoir interface and therefore contains information in addition to the conventional stacked seismic amplitudes. Trapping is especially relevant for the post-injection observations reported by Luth et al. [8]. The main CO_2-related seismic signature was confined to the target storage interval and no systematic evidence of overburden migration was observed. The apparent plume footprint was smaller than previously observed. This stabilization is consistent with progressive trapping, but the seismic data alone cannot resolve whether the change is due to residual trapping, dissolution, redistribution into thin layers, or some combination of these processes. Structural and stratigraphic trapping would thus be the most directly identifiable trapping mechanisms geophysically, especially when the reservoir architecture and caprock geometry are known independently.

2.3 Residual and Capillary Trapping

Residual trapping is fundamentally different from structural trapping in that immobilization occurs within the pore network, rather than by macroscopic geological closure. During drainage, the non-wetting CO 2 displaces the brine and forms a connected phase . During subsequent imbibition, brine reenters the pore system and disrupts the CO 2 phase through pore-scale displacement processes such as snap-off. The resulting disconnected clusters can be pinned by capillary forces

2.3.1 Evidence for the extent of residual trapping

Burnside and Naylor [24] compiled experimental relative-permeability and trapping measurements for CO 2 -brine and noted a large variation in residual trapping behavior. Their synthesis demonstrated that the range of reported experimental trapping efficiencies is broad, suggesting that the residual saturation is not characterized by a single universal value.
This conclusion is supported by a more recent synthesis by Zhang and Arif [21]. Residual trapping is a function of a combination of petrophysical, physicochemical, hydrodynamic and operational parameters. extrapolation of measured residual saturation from one formation to another can involve considerable uncertainty. Experimental evidence that residual trapping relates to sandstone properties was

provided by Ni et al. [23]. Corefloodiing experiments on several sandstone samples show that the residual trapping tendency decreases with porosity and increases with heterogeneity. This finding is particularly important from the perspective of geophysical interpretation as the same heterogeneity that affects seismic and electric resolution controls the amount and spatial distribution of immobilized CO2. Trevisan et al. [34] showed the impact of the spatial correlation structure of heterogeneous porous media on intermediate laboratory-scale capillary trapping. This shows that the trapping depends on the size as well as the spatial organization of the heterogeneity.

2.3.2 Seismic expression of capillary trapping

Ajo-Franklin et al. [14] showed that crosswell seismic tomography at Cranfield can image CO_2-induced reductions in P-wave velocity and determine saturation from a patchy-saturation model. The estimated saturation distribution was in good agreement with independent logging information, and lends support to the potential for quantitative monitoring with high resolution seismic methods. But the importance of accounting for patchiness is itself important. Effective elastic properties are influenced by fluid configuration at sub-seismic scale. Residual trapping exactly changes this configuration by converting a connected non-wetting phase to distributed isolated clusters. The complexity of the velocity–saturation relationships at Frio was also shown by Al Hosni et al. [16]. The observed change in P-wave velocity could not be fully explained using a simplistic conventional fluid-substitution treatment indicating pressure evolution, rock-fluid interaction or more complex saturation distributions may play a role in seismic response. These results suggest that a unique Gassmann-type saturation relationship may not be sufficient to estimate residual trapping in heterogeneous reservoirs.

2.3.3 Electrical detection of the residual CO_2

Additional support comes from the Ketzin ERT studies [9–13]. Usually the formation resistivity increases with increasing CO_2 saturation, because the saline formation water is a much better conductor of electricity than CO_2. Schmidt-Hattenberger et al. [9] showed that permanently installed electrical array can detect CO_2-related changes. Bergmann et al. [10] extended the monitoring geometry to surface-downhole ERT, which allowed a better spatial characterization of the reservoir resistivity changes. Later observations over long time periods [11–13] showed that permanent ERT systems can operate over multiyear periods, and can be calibrated to provide quantitative estimates of CO 2 saturation. Comparison with independent borehole log increased confidence in the inferred saturation. But ERT shares the same fundamental conceptual problem as seismic monitoring. It measures electrical response mostly related to saturation and brine connectivity. It does not directly measure if the CO_2 is capillary immobilized. Thus residual trapping has moderate geophysical detectability at the present time. Although it is often possible to determine the presence and saturation of CO_2, additional constraints from saturation history, flow modeling, hysteresis, pressure behavior and possibly pore-scale rock-physics relationships are necessary to show that the observed phase is disconnected and immobile.

2.4 Solubility Trapping

Solubility trapping is the transfer of molecular CO_2 from the free phase into formation brine. Dissolved CO 2 does not create a separate buoyant phase, so the potential for upward migration is greatly reduced . This process thus improves the security of long-term storage.

2.4.1 Diffusion and Density Driven Convection

Neufeld et al. [25] showed that dissolution can be significantly enhanced by density-driven convection in saline aquifers. As CO_2 dissolves into the brine near the free-CO_2/brine interface, the resultant solution becomes denser. This unstable configuration of denser fluid sitting on top of lighter brine causes

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downward convective fingers that substitute saturated fluid near the interface with relatively unsaturated brine, and perpetuate further dissolution. This process indicates that long term dissolution may not be described solely by molecular diffusion.

Soltanian et al. [35] extended this work to study the critical behavior of gravito-convective mixing and demonstrated that the onset of convective instability is governed by combined density, permeability and transport conditions.

2.4.2 Impact of reservoir heterogeneity

Heterogeneity brings in further complexity. Geological heterogeneity can influence CO_2-brine mixing and stable dissolution trapping, as experimentally shown by Agartan et al. [26]. Depending on the architecture, heterogeneous flow paths can increase fluid-fluid contact or alter convective development. Similarly, Gilmore et al. [27] have demonstrated that the dissolution rates in heterogeneous porous media are different from those predicted by homogeneous models. The fine-scale permeability structure changes the plume configuration and the interfacial area and thus affects the quantity and rate of CO_2 transfer into the brine. Wang et al. [28] investigated dissolution in randomly stratified systems and reported that geological uncertainty and stratification may have substantial effects on dissolution efficiency. This means that solubility trapping at reservoir scale is not only a thermodynamic solubility control. It is also a transport problem, determined by the efficiency of mixing of free CO_2 and unsaturated brine.

2.4.3 Geophysical detection of dissolved CO_2 is difficult

The main geophysical challenge is that dissolution wipes out the sharp contrast provided by the discrete free CO_2 phase. The difference between brine and CO_2-rich brine is usually much smaller than the difference between brine and free supercritical CO_2. The difficulty is exemplified by the post-injection observations at Ketzin [8]. The decrease in the apparent free-phase plume was consistent with processes such as dissolution, but seismic observations alone could not uniquely quantify the dissolved fraction. Gravity may provide another constraint, since dissolution changes fluid density and mass distribution [4,5], though spatial resolution is relatively poor. Combined seismic and electromagnetic modeling can improve estimates of the extent and saturation of the plume, according to Fawad and Mondol [19]. Such integration may be especially useful during the transition from free-phase to dissolved CO_2, where the seismic response is less diagnostic. But there is no direct technique to identify a volume of the reservoir containing "dissolution-trapped CO_2". Usually, solubility trapping has to be inferred from the disappearance of free-phase CO_2, changes in reservoir properties, mass balance, reservoir simulation, and geochemical information. Its geophysical detectability is thus to be rated low to moderate and mainly indirect.

2.5. Mineral trapping

Mineral trapping is the conversion of dissolved carbon to stable solid mineral phases. CO_2 dissolution lowers aqueous pH and increases dissolution of reactive minerals. Released cations such as Ca, Mg and Fe can react with carbonate species and precipitate carbonate minerals subsequently. Of the main trapping mechanisms, mineralization is the strongest way of long-term immobilization as carbon is incorporated into a solid phase [29,31–33]. But it is especially difficult to verify geophysically.

2.5.1 Controls on mechanisms of mineral trapping

Khandoozi et al. [29] also showed that mineral-trapping potential in sedimentary reservoirs is highly dependent on mineralogical composition, temperature, pressure, reactive surface area, fluid chemistry, and accessibility of reactive phases. So, sedimentary reservoirs can have very different rates and capacities for mineral fixation. Zhang and DePaolo [31] strongly stressed the formation dependence of mineralization rates. Reaction kinetics are not directly transferable between sedimentary reservoirs, basaltic formations, and other reactive lithologies. Mineralization in basalt, sandstone, carbonate and shale systems was reviewed by Kim et al. [32] and similarly showed that host-rock mineralogy controls reaction pathways and carbonate-forming potential. Basaltic formations are of special interest as shown by Raza et al. [33]. The abundance of reactive divalent-cation-bearing minerals they contain can support mineral carbonation rates much faster than those typically measured in quartz-rich sedimentary reservoirs.

2.5.2 Ketzin evidence

Klein et al. [30] studied long-term mineral trapping at Ketzin using a combination of geochemical modeling and reservoir simulation. Importantly, mineralization was predicted by the reactive modeling, and not directly observed by geophysical measurements. This distinction is important for interpreting the existing CCS monitoring literature . Ketzin has one of the most comprehensively monitored experimental CO2 reservoirs worldwide with seismic, ERT, borehole, pressure and geochemical data [6-13]. But even this large monitoring program did not produce a simple geophysical measurement that could be interpreted in a unique way as mineralized CO2.

2.5.3 Possible geophysical signatures

In theory, mineral dissolution and precipitation can alter:
• Porosity;
• pore interconnectivity
• porosity • permeability
• Frame stiffness
• Velocities of S and P waves;
• densidade;
attenuation;
• electrical conductivity

These changes provide the physical basis for geophysical sensitivity. But none of these is specific for mineralization. For example, an increase in seismic velocity may be caused by carbonate precipitation and cementation, but it may also be caused by pressure recovery, decreasing free-gas saturation, increasing effective stress, or mechanical compaction. Similarly, changes in electrical resistivity can be caused by mineral precipitation, changes in salinity, changes in temperature, redistribution of brine, or changes in saturation. Mineral trapping is therefore the least directly detectable mechanism at present by conventional field-scale geophysics. Geophysical observations may potentially provide supporting constraints but attribution requires integration with geochemistry, mineralogic measurements, reactive-transport simulation and long term baseline observations.

2.6 Rock-Physics Expression of Different CO_2 Trapping States

Rock physics provides the essential bridge between trapping mechanisms and geophysical observations. The fundamental interpretation sequence is:
CO_2 trapping process → pore-fluid/mineral configuration → physical-property change → geophysical measurement → inversion → inferred reservoir state.
Every stage introduces uncertainty.

2.6.1 Free phase vs. dissolved CO2

Free phase CO2 generally results in a large decrease in the effective fluid bulk modulus over brine. Thus, even a small gas or supercritical-CO2 saturation may have a strong influence on P-wave velocity. Conversely, dissolved CO2 stays in the aqueous phase and has much less elastic contrast. This explains why structural trapping is easily detectable seismically but solubility trapping is much more difficult.

2.6.2 Connected and disconnected CO_2
Residual trapping is a different problem. From the elastic property point of view, the connected mobile CO2 and disconnected residual CO2 can be modeled as free-phase CO2.
The difference is mainly in the spatial arrangement. Ajo-Franklin et al. [14] showed that assumptions of

patchy saturation influence seismic interpretation of saturation. As shown by Rasmusson et al. [22], residual trapping is governed by distribution and connectivity at the pore-scale. Taken together, these observations suggest that rock-physics models intended to identify trapping states should include phase topology, not simply average saturation.

2.6.3 Homogeneous and patchy saturation

Conventional fluid-substitution models assume effective equilibration or rather homogeneous fluid distributions. Geological reservoirs often do not satisfy this assumption. Capillary barriers, permeability contrasts, thin layering, and pore-scale trapping produce patchy saturation at scales from micrometers to meters. Depending on the seismic frequency and patch size, fluid-pressure equilibration may be incomplete, changing velocity and attenuation. Thus, two reservoirs with the same average CO 2 saturation may produce different seismic responses.

2.7 Can Geophysics Distinguish the Four Trapping Mechanisms?

The combined evidence from the original geophysical studies [1–20] and the mechanism-specific literature [21–35] allows a more defensible comparison of trapping-state detectability.

Table 2.1: Comparison of trapping-state detectability

Trapping state	**Principal physical characteristic**	**Likely geophysical response**	**Present ability to identify mechanism**
Mobile free CO_2	Connected non-wetting phase	Strong seismic and electrical contrast	High detectability of CO_2, mobility not always directly known
Structural/stratigraphic trapping	Free CO_2 accumulated beneath a known barrier	Strong seismic, resistivity and density anomaly	**High**
Residual/capillary trapping	Disconnected CO_2 ganglia	Saturation-dependent seismic/electrical response	**Moderate**
Solubility trapping	CO_2 dissolved in brine	Weak density, elastic and electrical changes	**Low–moderate**
Mineral trapping	Carbon incorporated into solid minerals	Slow changes in elastic, density and electrical properties	**Low**

The easiest to recognize are structural traps, since both the CO2 anomaly and the geological trap can often be imaged. Residual trapping is moderate. Geophysics can see the CO_2, but you need to know about saturation history and connectivity to know if it is disconnected." The inference of solubility trapping is mainly because the disappearance of free CO2 is not enough to prove dissolution. The mineral trapping is still largely reliant on geochemistry and reactive modeling, rather than direct geophysical verification. This results in a significant paradox: As the thermodynamic and physical security of stored CO2 increases, its direct geophysical detectability generally decreases. Free phase CO2 is arguably the most mobile but gives the strongest geophysical signal. Mineralized carbon is effectively sequestered, but may only result in subtle and non-unique changes in reservoir properties.

2.8 Synthesis and Implications for Monitoring

Collectively, the 35 studies show that geophysical monitoring has advanced substantially from simple plume detection to quantitative estimation of saturation and density. Sleipner time-lapse seismic data showed that plume migration and stratigraphic accumulation imaging is possible [1,2]. Later, seismic inversion provided estimates of saturation [3]. Gravity measurements limited density and mass changes [4, 5]. The advantages of multimethod monitoring at Ketzin, especially the combination of seismic and long-term ERT, have been demonstrated [6–13]. Rock-physics and to characterize at high resolution can be calibrated using crosswell and borehole seismic measurements, as shown by Cranfield and Frio [14–16]. Otway displayed increasing sophistication in time-lapse seismic and DAS monitoring [17,18], while combined electromagnetic approaches [19] and machine-learning inversion [20] demonstrate emerging directions for quantitative monitoring. The physical information that is necessary to interpret these measurements more carefully is contained in the literature on the specific mechanism. Pore-scale topology, wettability, saturation history and heterogeneity control the immobilization as demonstrated by residual trapping studies [21–24,34]. Studies of dissolution [25–28,35] indicate that stable trapping in water is controlled by thermodynamics and transport-driven mixing. Mineral-trapping research [29–33] indicates that permanent fixation depends on mineralogy and reaction kinetics that may evolve over timescales substantially longer than those of conventional monitoring campaigns. The main limitation is therefore no longer just the question of whether CO 2 can be detected. The more difficult question is whether a measured geophysical signal can be translated in a unique way into CO_2 state and mobility.

A strong interpretation of monitoring should therefore distinguish four levels of inference:
Level 1: Identification
Is there any evidence of CO_2 being injected?
Level 2 : Quantification
What is its approximate saturation? What is its volume, density or mass?
State characterization level 3
Is the CO_2 phase free, dissolved or mineralized?
Level 4: Mobility and trapping detection

Is free-phase CO_2 mobile, structurally immobilized, or residually immobilized? Geophysical methods are mature at Level 1, and increasingly capable at Level 2. Level 3 is still considerably more difficult, while level 4 represents one of the main open challenges in CO_2 storage geophysics. Future monitoring frameworks will have to integrate multiple physical observations with reservoir-process information. Seismic measurements can constrain plume geometry and elastic properties. ERT and electromagnetic measurements can constrain conductive-fluid distribution. Gravity can constrain density and mass. Pressure and well logging can provide local calibration; and geochemistry can provide evidence for dissolution and mineral reaction. These observations should then be combined with reservoir simulation and rock physics:
reservoir flow and trapping model → predicted CO_2 state → rock-physics transformation → predicted geophysical response → observed data → inversion/history matching → updated trapping-state estimate.

3. Geophysical Methods for Detection and Monitoring of Geological CO_2 Storage

Geophysical monitoring is central to the characterization and verification of geological CO_2 storage because injection modifies several measurable physical properties of the reservoir. Replacement of formation brine by free-phase CO_2 changes the effective compressibility, density, acoustic impedance, electrical conductivity, and, under some conditions, attenuation characteristics of the rock-fluid system. Simultaneously, injection-induced pressure changes modify effective stress and may alter seismic velocities independently of fluid substitution. The observed geophysical response therefore represents the combined influence of saturation, pressure, fluid distribution, reservoir architecture, and rock properties rather than a direct measurement of CO_2 itself. The studies reviewed in Sections 1 and 2 demonstrate that no single geophysical method provides complete information about the evolving storage system [1–20]. Surface seismic methods provide excellent spatial coverage and sensitivity to elastic changes;

borehole seismic techniques improve vertical resolution; electrical and electromagnetic methods respond strongly to displacement of conductive brine; gravity observations constrain density and mass redistribution; and permanent fiber-optic systems provide improved temporal sampling [3–20]. Consequently, the choice of monitoring technique must be related not only to reservoir depth and geology but also to the particular storage property being investigated. This section evaluates the principal geophysical techniques used for CO_2 storage monitoring, with particular emphasis on their sensitivity, spatial and temporal resolution, quantitative capability, and relevance to identification of different trapping states.

3.1 Rock-Physics Basis of Geophysical CO_2 Monitoring

Rock physics provides the fundamental connection between reservoir processes and geophysical measurements. Geophysical instruments measure seismic velocity, impedance, electrical resistivity, density, or related properties rather than CO_2 saturation or trapping mechanism directly. Interpretation therefore requires a model describing how changes in reservoir fluids and pressure modify measurable physical properties.

A simplified interpretation pathway is:

CO_2 injection → saturation/pressure/fluid configuration change → rock-property change → geophysical response → inversion → reservoir-state estimate

Uncertainty at any stage propagates into the final interpretation.

3.1.1 Elastic response to CO_2-brine substitution

The seismic response of a porous reservoir depends on the elastic properties of both the solid frame and pore fluids. Replacement of relatively incompressible brine by more compressible CO_2 generally decreases the effective saturated bulk modulus and consequently reduces P-wave velocity.

P-wave velocity can be expressed as:

$$V_p = \sqrt{\frac{k + \frac{4}{3}G}{\rho}}$$

where K is the saturated bulk modulus, G is the shear modulus, and ρ is bulk density.

S-wave velocity is:

$$V_s = \sqrt{\frac{G}{\rho}}$$

Because pore fluids primarily influence the bulk modulus rather than the shear modulus, P-wave velocity is generally more sensitive to CO_2 substitution than S-wave velocity.

This explains why P-wave velocity reduction, reflection-amplitude variation, travel-time delay, and acoustic-impedance change constitute major seismic indicators of CO_2 injection [1–3,14–18].

The bulk acoustic impedance is:

$$Z = \rho Vp$$

and the normal-incidence reflection coefficient between two layers is approximately:

$$R = \frac{Z_2 - Z_1}{Z_2 - Z_1}$$

Changes in reservoir impedance after injection therefore modify reflection amplitude. Time-lapse seismic monitoring exploits this difference by comparing a baseline survey with one or more repeat surveys.

3.1.2 Gassmann fluid substitution

Gassmann's equations are widely used to estimate how fluid substitution affects saturated rock properties. The saturated bulk modulus may be expressed as:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_m}\right)^2}{\frac{\phi}{K_f} + \frac{1-\phi}{K_m} - \frac{K_{dry}}{K_m^2}}$$

Where K_{dry} is the dry-frame bulk modulus, Km is the mineral modulus, K_f is the effective pore-fluid modulus, and ϕ is porosity.

For a mixed brine-CO_2 pore fluid, the effective fluid modulus is commonly approximated using a Reuss-type relationship:

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$$\frac{1}{K_f} = \frac{S_{CO_2}}{K_{CO_2}} + \frac{1 - S_{CO_2}}{K_b}$$

Where S_{CO2} represents CO_2 saturation and Kb is the brine bulk modulus.

These relationships explain the strong sensitivity of seismic velocity to relatively small quantities of free CO_2. However, field observations indicate that simple Gassmann-based relationships are not always sufficient. At Frio, Al Hosni et al. [16] found that the observed time-lapse P-wave velocity reduction could not be explained completely by conventional fluid-substitution calculations. Pressure effects, fluid distribution, and CO_2-brine-rock interactions were proposed as possible additional controls.

Consequently, a simple conversion of seismic velocity change into CO_2 saturation may produce significant uncertainty.

3.1.3 Homogeneous and patchy saturation

Fluid distribution represents one of the most important uncertainties in seismic interpretation.

A homogeneous saturation model assumes that CO_2 and brine are effectively mixed at scales sufficiently small for pressure equilibration to occur during wave propagation. In contrast, patchy saturation occurs when CO_2-rich and brine-rich regions remain spatially separated at relevant scales. Ajo-Franklin et al. [14] demonstrated the importance of patchy-saturation rock physics when interpreting crosswell seismic observations at Cranfield. Their results showed that sub-wavelength fluid configuration influences the relationship between measured velocity and inferred CO_2 saturation. This has direct relevance to trapping-state identification. Residual trapping transforms connected CO_2 into spatially distributed disconnected ganglia [21–24]. Therefore, two reservoir volumes containing identical average CO_2 saturation may have different seismic responses depending on phase topology and patch size.

3.1.4 Pressure effects

CO_2 injection changes reservoir pressure in addition to saturation. Increased pore pressure reduces effective stress and may alter the elastic properties of the rock frame. Importantly, pressure perturbations may propagate considerably farther than the free-phase CO_2 plume.

A time-lapse seismic anomaly can therefore contain contributions from:

$$\Delta V_P = f(\Delta S_{CO_2}, \Delta P, \Delta\sigma, \text{fluid distribution}, \text{rock p}$$

Where ΔP represents pressure change and Δσ represents stress variation.

Separating pressure and saturation effects is therefore essential for quantitative interpretation.

3.1.5 Electrical response

Electrical methods exploit the large conductivity difference between saline formation water and CO_2. Bulk formation conductivity is often related to water saturation using Archie's law:

$$\rho_t = a\rho_w\phi^{-m}S_w^{-n}$$

Where ρt is bulk formation resistivity, ρw is brine resistivity, Sw is water saturation, m is the cementation exponent, n is the saturation exponent, and a is an empirical constant.

Because

$$S_{CO_2} = 1 - S_w,$$

Replacement of brine by CO_2 generally increases resistivity.

The Ketzin studies [9–13] demonstrated that these changes can be detected repeatedly and, with appropriate calibration, converted into estimates of CO_2 saturation. However, Archie's relationship is affected by clay content, salinity, temperature, pore connectivity, and surface conduction. Electrical interpretation therefore has uncertainties analogous to those associated with seismic rock physics.

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Table 3.1. Principal reservoir changes and corresponding geophysical responses

Reservoir change	**Physical consequence**	**Expected geophysical response**	**Principal method**
Brine → free CO_2	Reduced fluid bulk modulus	Lower VP, impedance change	Seismic
Increasing CO_2 saturation	Elastic-property change	Amplitude/travel-time variation	4D seismic
Brine → CO_2	Reduced conductivity	Increased resistivity	ERT/EM
Brine displacement	Density reduction	Gravity decrease	Gravity
Pressure increase	Effective-stress reduction	Velocity/impedance change	Seismic
Patchy CO_2 distribution	Local pressure disequilibrium	Dispersion/attenuation	Seismic
Residual CO_2	Disconnected free phase	Saturation/configuration-dependent response	Seismic + ERT
Dissolved CO_2	Brine density/composition change	Weak elastic/electrical/density response	Multiphysics
Mineral precipitation	Frame/mineral-property change	Potential velocity/resistivity/density change	Long-term multiphysics

3.2 Time-Lapse Surface Seismic Monitoring

Time-lapse, or 4D, seismic monitoring is currently the most established reservoir-scale geophysical method for geological CO_2 storage. A baseline 3D seismic survey is acquired before injection and compared with repeat surveys acquired during or after injection.

Differences between surveys can reveal changes in reflection amplitude, travel time, phase, attenuation, and acoustic impedance.

3.2.1 CO_2 plume imaging

The Sleipner project provides the best-known field demonstration [1–3]. Repeated seismic surveys revealed multiple high-amplitude reflections produced by free-phase CO_2 accumulating beneath thin intra-reservoir mudstone layers. The strong time-lapse signal resulted from the contrast between brine-saturated sandstone and sandstone containing free CO_2. This enabled the spatial evolution of the plume to be monitored over successive injection stages. A particularly important result from Sleipner is that seismic imaging resolved not merely the outer plume boundary but also internal stratigraphic control. Consequently, 4D seismic can provide information about the geological mechanisms responsible for plume confinement.

3.2.2 Travel-time effects

CO_2-induced velocity reduction can cause measurable time delays in seismic waves passing through the plume. These travel-time changes provide information complementary to reflection amplitude. If the velocity changes from V0 to V1 over thickness h, the approximate two-way travel-time difference can be expressed as:

$$\Delta t = 2h\left(\frac{1}{V_1} - \frac{1}{V_0}\right)$$

Travel-time delays can therefore provide constraints on integrated velocity changes even when individual thin CO_2 layers cannot be completely resolved.

3.2.3 AVO and quantitative interpretation

Ivandic et al. [7] applied time-lapse amplitude-versus-offset analysis at Ketzin to extract additional information about CO_2 saturation. Because reflection amplitude varies with incidence angle according to contrasts in P-wave velocity, S-wave velocity, and density, AVO analysis provides more information than normal-incidence amplitude alone.

However, quantitative AVO interpretation requires good repeatability and accurate knowledge of reservoir rock properties.

3.3 Vertical Seismic Profiling and Crosswell Seismic Tomography

Surface seismic provides broad spatial coverage, but borehole seismic techniques can achieve higher resolution around monitoring wells.

3.3.1 Vertical seismic profiling

VSP places receivers within a borehole while seismic energy is generated at or near the surface. Because the receivers are located closer to the reservoir, propagation through the highly heterogeneous near-surface region is reduced. VSP can therefore provide improved vertical resolution and more accurate travel-time information than conventional surface seismic in some settings. At Frio, time-lapse VSP observations showed substantial P-wave velocity changes associated with CO_2 injection [16]. These observations were particularly valuable for evaluating rock-physics relationships between CO_2 saturation and seismic velocity.

3.3.2 Crosswell seismic tomography

Crosswell tomography places sources and receivers in separate wells, allowing seismic waves to travel directly through the interwell reservoir. Ajo-Franklin et al. [14] applied high-resolution time-lapse crosswell tomography at Cranfield and identified CO_2-related velocity reductions. The inferred saturation distribution was compared with independent borehole measurements, demonstrating the potential for quantitative characterization. Crosswell seismic generally provides considerably higher spatial resolution than surface seismic because of the shorter propagation paths and higher usable frequencies. However, the technique is restricted to the region between wells. Its effectiveness therefore decreases for large storage reservoirs with widely separated monitoring wells. Daley et al. [15] further demonstrated that active-source crosswell systems can support frequent measurements during injection, improving temporal characterization of plume evolution.

Table 3.2. Comparison of major seismic monitoring configurations

Method	**Spatial coverage**	**Resolution**	**Temporal repeatability**	**Main strength**	**Main limitation**
Surface 4D seismic	High	High	Moderate	Reservoir-scale plume imaging	Cost and repeatability
VSP	Moderate	High	High	Detailed reservoir response	Borehole required
Crosswell tomography	Low	Very high	High	Quantitative interwell imaging	Limited spatial coverage
DAS-VSP	Moderate–high	High	Very high	Permanent/repeatable monitoring	Directional sensitivity
Passive seismic	High	Event dependent	Continuous	Geomechanical surveillance	Does not directly image saturation

3.4 Distributed Acoustic Sensing

Distributed acoustic sensing represents one of the most important recent developments in CO_2 monitoring. DAS uses optical fibers as dense arrays of strain-sensitive seismic receivers. A single fiber may effectively provide thousands of measurement channels along a borehole.

3.4.1 Advantages of permanent fiber-optic monitoring

Conventional repeated seismic surveys require receiver redeployment, which introduces positioning and coupling differences between baseline and repeat surveys. Permanently installed fiber-optic cables reduce these sources of non-repeatability. This is particularly important for CO_2 monitoring because time-lapse signals can be small relative to differences caused by acquisition geometry. DAS also allows frequent monitoring without repeatedly deploying conventional downhole geophones.

3.4.2 Otway observations

Pevzner et al. [17] used realistic 4D seismic modeling to evaluate the detectability of a relatively small CO_2 plume at Otway. Their work showed that the expected time-lapse response should remain detectable under realistic acquisition and noise conditions. Yurikov et al. [18] subsequently demonstrated multi-well 4D DAS-VSP monitoring during CO_2 injection. Multiple borehole fibers produced broadly consistent plume images, demonstrating that permanent fiber-optic monitoring can characterize reservoir-scale fluid changes. The observations also demonstrated that acquisition geometry, anisotropy, and lateral velocity heterogeneity affect the reconstructed plume.

3.4.3 Limitations

DAS does not measure particle motion in the same manner as conventional three-component geophones. Sensitivity depends strongly on the orientation of the fiber relative to the incident wavefield. Processing and interpretation therefore require consideration of fiber geometry, gauge length, directional response, and coupling. Nevertheless, the ability to perform frequent repeat surveys makes DAS particularly attractive for identifying temporal transitions between active plume migration and stabilization.

3.5 Electrical Resistivity Tomography

ERT provides a fundamentally different sensitivity from seismic methods. Whereas seismic techniques respond primarily to elastic properties, ERT responds to electrical conductivity. This distinction makes the two approaches highly complementary.

3.5.1 Ketzin field evidence

Ketzin represents one of the most comprehensive field demonstrations of ERT for CO_2 monitoring [9–13]. Schmidt-Hattenberger et al. [9] demonstrated that permanently installed downhole electrodes could detect changes associated with CO_2 migration. Bergmann et al. [10] subsequently combined surface and downhole electrodes to improve spatial coverage. Long-duration monitoring [11–13] demonstrated that the permanent electrical system could operate reliably over several years and that calibrated resistivity changes could be converted into quantitative saturation estimates. An important result was the broad agreement between ERT-derived saturation estimates and independent borehole logging [13].

3.5.2 Strengths and limitations

ERT has several advantages:

- strong sensitivity to brine displacement;
- potential permanent installation;
- relatively frequent monitoring;
- complementary sensitivity to seismic methods;
- potential quantitative saturation estimation.

However, resolution decreases away from electrodes, particularly in deep reservoirs. Interpretation is also influenced by brine salinity, temperature, clay content, surface conduction, and reservoir anisotropy. ERT is therefore particularly useful when wells already exist and permanent monitoring infrastructure can be installed.

3.6 Controlled-Source Electromagnetic Monitoring

Controlled-source electromagnetic methods extend electrical monitoring to larger spatial scales by generating electromagnetic fields and measuring their interaction with subsurface conductivity structures. Because CO_2 replacement of brine increases resistivity, CSEM can potentially detect reservoir-scale CO_2 accumulations. Fawad and Mondol [19] investigated integrated seismic and electromagnetic monitoring and demonstrated that the two datasets provide complementary information about plume extent and saturation. Their analysis suggested that repeated electromagnetic measurements may provide a lower-cost component of long-term monitoring when combined with seismic constraints. However, electromagnetic inversion generally provides lower spatial resolution than seismic imaging. Resolution decreases with depth, and inversion can be strongly non-unique. The principal value of EM monitoring is therefore likely to lie in **multiphysics integration rather than independent high-resolution plume imaging**.

3.7 Gravity Monitoring

Gravity monitoring exploits density changes produced when relatively dense formation brine is displaced by lower-density CO_2.

The gravity change produced by a reservoir can be conceptualized as:

$$\Delta g \propto G \int_V \frac{\Delta\rho(\mathbf{r})}{r^2} dV$$

Where G is the gravitational constant and $\Delta\rho$ represents the density change.

3.7.1 Sleipner observations

Alnes et al. [4] demonstrated that repeated gravity measurements at Sleipner could constrain the in situ density of stored CO_2 when interpreted together with other reservoir information.

Zumberge et al. [5] demonstrated the measurement precision achievable with repeated seafloor gravity and pressure observations.

These studies established gravity as an important complementary monitoring method.

3.7.2 Advantages and Limitations

Unlike seismic measurements, gravity responds directly to density and mass redistribution. It can therefore provide information about stored CO_2 mass that is comparatively independent of elastic rock-physics assumptions. The primary limitation is poor spatial resolution. Many different subsurface density distributions can generate similar gravity anomalies. Consequently, gravity is most powerful when plume geometry has already been constrained by seismic or other measurements.

3.8 Full-Waveform Inversion and Quantitative Seismic Imaging

Conventional seismic interpretation relies heavily on reflection amplitude and travel-time differences. Full-waveform inversion attempts to use substantially more of the recorded wavefield. FWI iteratively updates a subsurface model to minimize the difference between observed and simulated seismic data:

$$\Phi(m) = \frac{1}{2} \| d_{obs} - d_{cal}(m) \|^2$$

Where m represents the subsurface model, d_{obs} the observed data, and d_{cal} the simulated data.

Yan et al. [3] demonstrated how seismic tomography combined with rock-physics inversion can move monitoring toward quantitative saturation estimation. FWI potentially provides higher-resolution velocity models than conventional travel-time tomography, making it particularly attractive for identifying relatively subtle time-lapse changes. Nevertheless, FWI remains computationally intensive and strongly dependent on acquisition geometry, starting models, data quality, and physical assumptions. Most importantly, obtaining an accurate velocity model does not itself determine trapping mechanism. Rock-physics interpretation remains necessary.

3.9 Machine Learning and Data-Driven Inversion

The increasing volume of time-lapse geophysical data has encouraged application of machine learning to CO_2 monitoring. Leong et al. [20] developed SeisCO2Net to estimate CO_2 saturation maps directly from time-lapse seismic data. Because sufficiently large labeled field datasets are unavailable, synthetic training examples were generated using geological, reservoir-flow, rock-physics, and seismic models before transfer learning was applied to field observations.

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This approach demonstrates a potentially important development: rapid mapping from seismic observations to reservoir properties without performing every conventional inversion stage separately. However, machine learning does not remove physical non-uniqueness. If the training models represent only CO_2 saturation but do not include capillary hysteresis, pressure variation, patchy saturation, dissolution, and mineral reactions, the network cannot reliably distinguish these processes in field data. Machine learning should therefore complement rather than replace physics-based interpretation.

3.10 Integrated and Multi-physics Geophysical Monitoring

The literature reviewed here strongly suggests that no individual geophysical method is sufficient for comprehensive trapping-state characterization.

Different methods measure different physical properties:

Seismic → elastic properties
ERT/EM → electrical properties
Gravity → density and mass
Well logging → localized saturation and lithology
Pressure monitoring → reservoir hydraulic response
Geochemistry → dissolved and reacted CO_2

Their integration can therefore reduce non-uniqueness.

For example, suppose seismic observations indicate a reduction in P-wave velocity. Several explanations are possible, including increased CO_2 saturation or pressure-related changes. If ERT simultaneously indicates increasing resistivity within the same volume, the interpretation of brine displacement by CO_2 becomes substantially stronger. If gravity observations additionally constrain the associated density change, the range of permissible CO_2 saturation and density models can be reduced further.

This can be expressed conceptually as:

$$P(m|D_s, D_e, D_g) \propto P(D_s, D_e, D_g|m)P(m$$

Where Ds, De, and Dg represent seismic, electrical, and gravity observations and m represents the reservoir model.

Integrated interpretation therefore transforms several individually non-unique measurements into a more constrained reservoir-state estimate.

Table 3.3. Comparative assessment of major geophysical techniques

Method	**Primary sensitivity**	**Spatial resolution**	**Temporal resolution**	**CO_2 saturation capability**	**Relative cost**	**Major limitation**
4D surface seismic	Elastic properties	High	Moderate	High	High	Pressure/saturation ambiguity
VSP	Elastic properties	High	High	High	Moderate–high	Borehole dependence
Crosswell seismic	Elastic properties	Very high	High	Very high locally	High	Small investigation volume
DAS-VSP	Dynamic strain/seismic waves	High	Very high	High	Moderate after installation	Directional response
ERT	Electrical resistivity	Moderate	High	High near electrodes	Moderate	Resolution decreases with distance

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Method	Primary sensitivity	Spatial resolution	Temporal resolution	CO_2 saturation capability	Relative cost	Major limitation
CSEM	Conductivity/resistivity	Moderate–low	Moderate–high	Moderate	Moderate	Non-unique inversion
Gravity	Density/mass	Low	Moderate	Indirect	Moderate	Poor spatial resolution
Passive seismic	Geomechanical events	Variable	Continuous	Very low	Moderate	Does not directly measure saturation

Table 3.4. Suitability of geophysical methods for different trapping states

Method	Structural trapping	Residual trapping	Solubility trapping	Mineral trapping
4D seismic	Excellent	Moderate	Low	Low
VSP/crosswell	Excellent	Moderate–high	Low	Low
DAS-VSP	Excellent	Moderate	Low	Low
ERT	Excellent	Moderate–high	Low–moderate	Low
CSEM	Good	Moderate	Low–moderate	Low
Gravity	Good	Low	Moderate	Low–moderate
Geophysical integration	Excellent	High potential	Moderate potential	Moderate potential
Geophysics + geochemistry	Excellent	High	High	**Highest potential**

The classifications in Table 3.4 should be interpreted as **relative qualitative assessments synthesized from the reviewed literature**, not experimentally measured numerical rankings.

3.11 Comparative Evaluation and Method Selection

The results discussed above demonstrate that method selection should depend on the monitoring objective rather than on a universal hierarchy of geophysical techniques. For **reservoir-scale plume geometry**, 4D surface seismic provides the strongest combination of spatial coverage and resolution. For **high-resolution saturation characterization near wells**, crosswell seismic and VSP provide superior local information. For **frequent permanent monitoring**, DAS and permanent ERT are particularly promising. For **independent mass and density constraints**, gravity provides information unavailable from seismic methods. For **fluid-saturation constraints complementary to seismic imaging**, ERT and CSEM are particularly valuable. The qualitative comparison can be visualized as follows. The scores below are a **conceptual synthesis on a 1–5 scale**, where 5 represents greater relative capability. They are not measured performance data and should be presented in the paper as a conceptual comparison rather than experimental results.

Relative capability of major CO_2 monitoring methods:

Conceptual literature-based comparison on a 1–5 scale. Scores are qualitative, not measured performance data. 5 = relatively strongest capability for the stated monitoring objective.

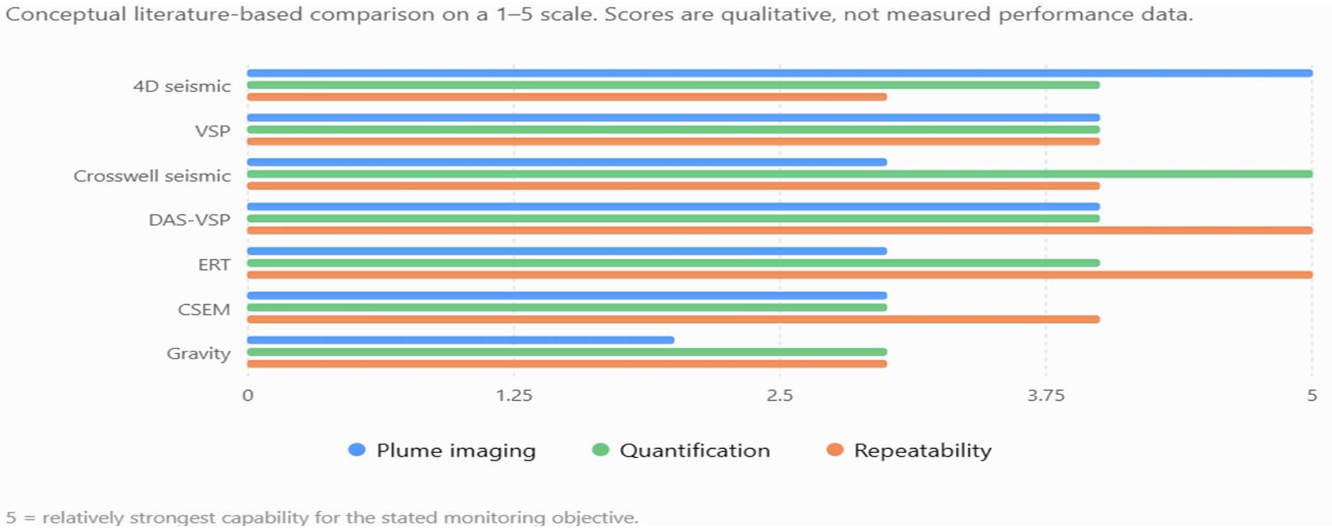

Figure 3.1. Conceptual comparison of the relative plume-imaging, quantitative-characterization, and repeatability capabilities of major geophysical techniques used for geological CO_2 monitoring. The ranking is a qualitative synthesis of the reviewed literature and is intended for method comparison rather than as measured field-performance data.

A second conceptual figure is useful for illustrating one of the central arguments of this review: storage security and geophysical detectability do not necessarily evolve in the same direction. Conceptual evolution of trapping security and geophysical detectability. Illustrative progression from mobile free-phase CO_2 toward mineralized carbon. Values represent conceptual relative levels, not experimental measurements. The figure illustrates the monitoring paradox discussed in Chapters 2 and 3.

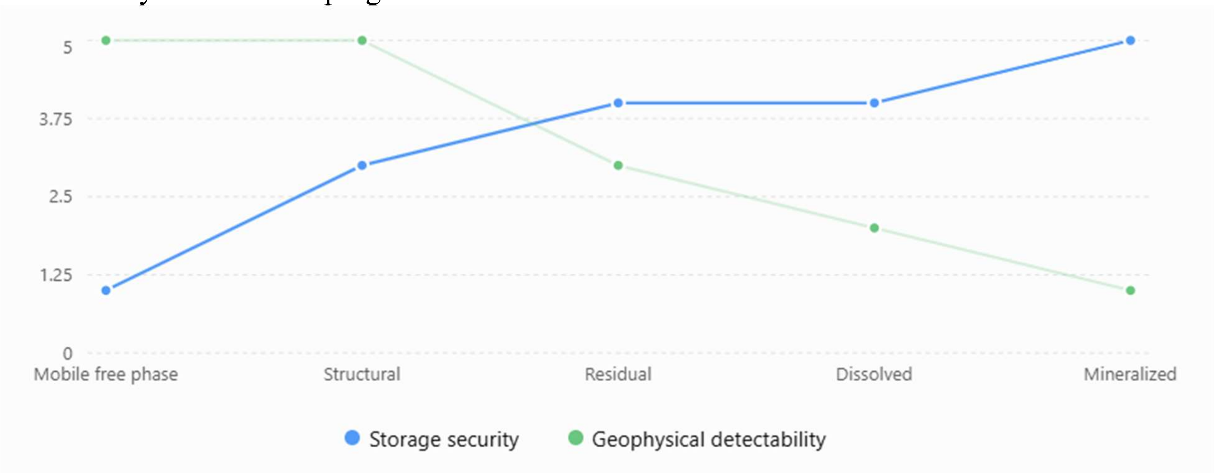

Figure 3.2. Conceptual relationship between increasing CO_2 storage security and decreasing direct geophysical detectability during progression from mobile free-phase CO_2 toward mineral trapping. Values are illustrative

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qualitative rankings derived from the synthesis of trapping and monitoring literature, not quantitative experimental measurements.

Figure 3.2 highlights an important issue. Conventional geophysical monitoring performs best when CO_2 exists as a distinct free phase because fluid substitution generates large elastic and electrical contrasts. As CO_2 becomes residually trapped, dissolved, and ultimately mineralized, its mobility decreases but the direct contrast relative to the surrounding reservoir also generally decreases. The monitoring objective must consequently evolve from direct plume imaging toward integrated inference.

3.12 Current Limitations in Quantitative Geophysical Monitoring

Despite substantial technological progress, several limitations prevent geophysical observations from providing unique trapping-state estimates.

First, **geophysical inversion is inherently non-unique**. Different combinations of saturation, pressure, porosity, lithology, and fluid distribution may generate similar observations.

Second, **spatial resolution differs among techniques**. Surface seismic can resolve reservoir-scale structures but not pore-scale ganglia, while borehole techniques provide high resolution over comparatively limited volumes.

Third, **temporal resolution varies considerably**. Conventional 3D seismic surveys may be separated by months or years, potentially missing short-term redistribution. Permanent DAS and ERT systems can partially address this problem.

Fourth, **rock-physics uncertainty directly affects saturation estimation**. The results from Cranfield and Frio [14,16] demonstrate that patchy saturation, pressure effects, and rock-fluid interaction must be considered when converting velocity changes into saturation.

Fifth, **detectability decreases as CO_2 becomes more securely immobilized**. This limitation is particularly important for dissolution and mineral trapping.

Finally, geophysical monitoring has a fundamental scale problem. Residual trapping occurs at pore scale, whereas most field measurements represent effective properties over meters to hundreds of meters. Linking these scales requires digital rock physics, pore-network modeling, upscaling, and reservoir simulation [21–24,34].

3.13 Chapter Synthesis

The reviewed studies demonstrate that modern geophysical monitoring provides a powerful framework for detecting and characterizing geological CO_2 storage. Surface 4D seismic remains the principal reservoir-scale plume-imaging technique, as demonstrated most clearly at Sleipner and Ketzin [1–3,6–8]. VSP and crosswell tomography provide higher-resolution characterization around monitoring wells [14–16], while DAS offers increasingly attractive opportunities for permanent and highly repeatable seismic surveillance [17,18]. Electrical monitoring provides complementary sensitivity to pore-fluid substitution. Long-term Ketzin observations demonstrate that permanent ERT can detect CO_2 migration and support quantitative saturation estimation [9–13]. CSEM extends electrical sensitivity toward larger spatial scales and may be particularly useful when integrated with seismic observations [19]. Gravity provides an independent constraint on density and mass redistribution [4,5]. The central limitation shared by these techniques is that they measure physical properties rather than trapping mechanisms. Quantitative seismic or electrical inversion can estimate CO_2 saturation, but saturation does not uniquely determine mobility. Residually trapped and connected CO_2 may produce similar bulk responses; dissolved CO_2 generates comparatively weak signals; and mineralized carbon is unlikely to be uniquely identifiable from conventional geophysical observations alone.

Accordingly, the progression of monitoring capability can be summarized as:

plume detection → plume delineation → saturation estimation → multiphysics characterization → trapping-state inference.
The first three stages have been demonstrated successfully at several field sites. The final stage remains an active research challenge. The most promising future framework is therefore not a single superior geophysical method but an integrated system combining:

4D seismic/DAS + ERT/EM + gravity + borehole measurements + pressure + geochemistry + reservoir simulation + rock physics.
Such integration is particularly important for the central objective of this review. The future of geological CO_2 monitoring lies not merely in producing increasingly detailed images of a plume, but in transforming multiple geophysical observations into defensible estimates of **CO_2 saturation, physical state, mobility, and trapping mechanism**. Chapter 4 therefore examines how far this objective has been achieved in major field-scale storage projects and what the collective evidence from Sleipner, Ketzin, Frio, Cranfield, and Otway reveals about the practical ability of geophysics to verify long-term CO_2 trapping

4. Field Applications, Integrated Monitoring, and Critical Assessment

Field-scale CO_2 storage projects provide the most important test of whether geophysical monitoring concepts developed through laboratory experiments, rock-physics models, and numerical simulations can function under realistic geological conditions. Unlike controlled laboratory systems, field reservoirs are affected by complex stratigraphy, heterogeneous permeability, uncertain fault behavior, variable well geometry, imperfect repeatability of geophysical surveys, and incomplete knowledge of the initial reservoir state. Consequently, field observations are essential for evaluating both the strengths and the practical limitations of different monitoring approaches. The most extensively studied projects, including Sleipner, Ketzin, Frio, Cranfield, and the CO2CRC Otway site, collectively demonstrate that geophysical techniques can detect injected CO_2, delineate plume migration, estimate saturation under favorable conditions, and verify that the plume remains within the intended storage interval [1–20]. However, these projects also show that geophysical monitoring is substantially more successful at detecting free-phase CO_2 than at directly identifying residual, dissolved, or mineralized fractions. A comparison of these projects therefore provides an opportunity to evaluate how different monitoring strategies perform across geological settings and to assess whether geophysical observations can progress from plume detection toward trapping-state characterization.

4.1 Sleipner CO_2 Storage Project

The Sleipner project in the Norwegian sector of the North Sea is one of the most extensively documented examples of industrial-scale geological CO_2 storage. CO_2 separated from produced natural gas has been injected into the Utsira Sand, a highly porous and permeable saline formation overlain by a regional sealing unit. Because repeated high-quality seismic surveys were acquired during storage operations, Sleipner became a benchmark site for development of time-lapse seismic monitoring.

4.1.1 Time-lapse seismic imaging of plume evolution

Arts et al. [1] demonstrated that repeated seismic data could clearly identify CO_2-related changes within the Utsira Sand. The time-lapse response was characterized by multiple strong reflections that developed after injection began. These reflections were interpreted as accumulations of CO_2 beneath thin intra-reservoir shale layers.
The observations provided direct evidence that plume migration was strongly influenced by stratigraphic heterogeneity. Rather than migrating as a single homogeneous body toward the top seal, CO_2 accumulated at multiple vertical levels. The reservoir therefore behaved as a layered trapping system in which individual barriers temporarily restricted upward migration. This result has several

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implications for monitoring. First, 4D seismic can provide information not only on plume extent but also on the geological controls responsible for plume geometry. Second, thin stratigraphic barriers may play a significant role in storage security even when they are not perfectly impermeable. Third, plume architecture is inherently three-dimensional and therefore difficult to characterize using sparse well observations alone.

4.1.2 Quantitative plume interpretation

Chadwick et al. [2] extended the Sleipner interpretation by examining time-lapse amplitudes and travel-time effects quantitatively. The study demonstrated that seismic data could be used to estimate plume thickness and lateral extent. However, conversion from seismic response to CO_2 saturation and volume remained uncertain. Thin-bed tuning represented one of the main difficulties. Individual CO_2 layers may be thinner than the dominant seismic wavelength, causing reflections from their upper and lower boundaries to interfere. Consequently, observed seismic amplitude does not necessarily scale linearly with layer thickness or CO_2 saturation. This problem illustrates an important distinction between qualitative and quantitative monitoring. A time-lapse anomaly can demonstrate the presence of CO_2 with high confidence even when the exact saturation and mass cannot be determined uniquely. Yan et al. [3] addressed this challenge using seismic tomography and rock-physics inversion. Their results showed that quantitative saturation estimates could be derived from velocity changes, although the estimates depended strongly on assumptions concerning fluid distribution and rock physics. The Sleipner data therefore illustrate a hierarchy of monitoring confidence:

high confidence in plume presence → strong confidence in plume geometry → moderate confidence in local saturation → lower confidence in specific trapping state.

4.1.3 Implications for trapping-state assessment

Sleipner provides strong evidence for structural and stratigraphic trapping. Free-phase CO_2 accumulations are directly associated with known geological barriers, and repeated surveys show persistent plume confinement within the intended storage interval. However, Sleipner also illustrates the limitations of geophysical interpretation. Seismic monitoring readily detects free-phase CO_2, but it does not directly determine how much of the injected CO_2 has become residually trapped or dissolved. A decrease in seismic response could represent dissolution, redistribution into thinner layers, reduction in saturation, or changes below seismic resolution. Thus, Sleipner demonstrates high confidence in **containment and plume geometry**, but more limited confidence in **mechanism-specific partitioning**.

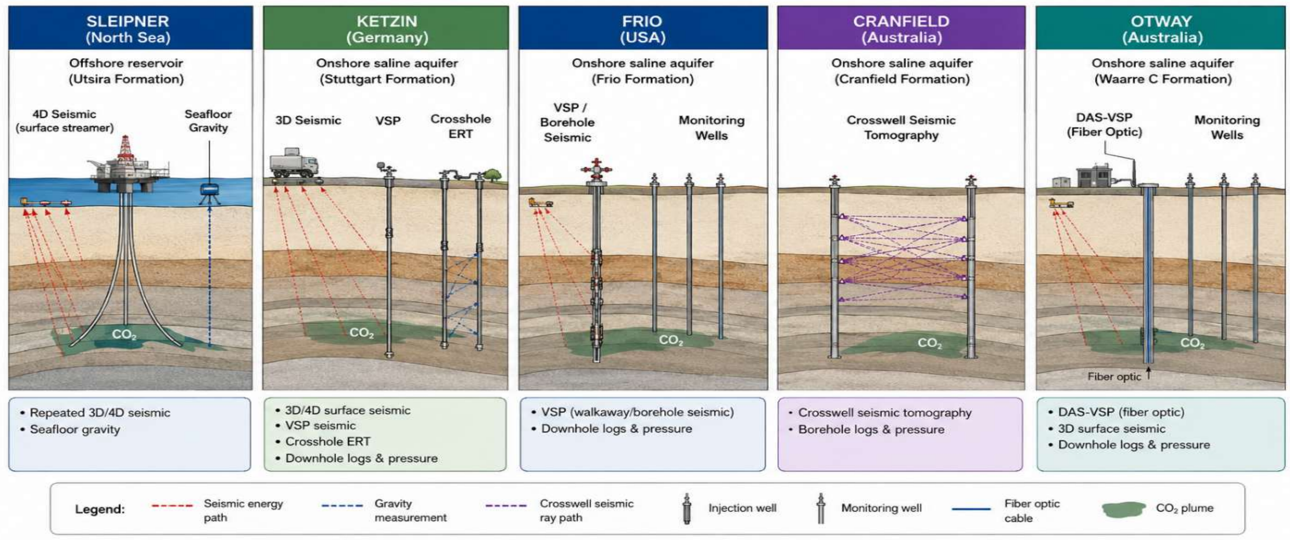

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Figure 4.1. Conceptual comparison of geophysical monitoring configurations applied at the Sleipner, Ketzin, Frio, Cranfield and CO2 storage sites. The project illustrate the evolution from repeated surface surveys toward integrated borehole and permanent fiber-optic monitoring.

4.2 Ketzin CO_2 Storage Project

The Ketzin pilot site in Germany represents one of the most comprehensive experimental CO_2 monitoring programs. Unlike Sleipner, which primarily relied on surface seismic and gravity, Ketzin employed a combination of surface seismic, VSP, crosshole methods, electrical resistivity tomography, borehole logging, and numerical modeling [6–13]. This multimethod approach makes Ketzin particularly valuable for evaluating integrated monitoring.

4.2.1 Seismic monitoring

Bergmann et al. [6] summarized the application of multiple geophysical techniques at Ketzin and demonstrated that repeated seismic surveys successfully detected changes associated with CO_2 migration. The plume generally remained concentrated near the injection interval and migrated preferentially along permeable reservoir layers. Seismic amplitude and velocity changes provided information about plume extent and reservoir heterogeneity. Ivandic et al. [7] applied time-lapse AVO analysis to estimate CO_2 saturation. By analyzing the dependence of reflection amplitude on incidence angle, the study extracted additional elastic information compared with conventional stacked seismic data. The results supported the feasibility of quantitative saturation estimation but also highlighted uncertainty arising from rock-physics assumptions and limited resolution.

4.2.2 Post-injection monitoring

Lüth et al. [8] evaluated seismic changes after injection ceased. A clear CO_2-related reflection remained within the storage interval, and no systematic seismic evidence indicated migration into the overburden. The apparent lateral plume extent decreased compared with earlier surveys. Several explanations were considered, including dissolution, redistribution into thin reservoir layers, and pressure-related changes. This observation is highly relevant to trapping-state interpretation. A reduction in visible free-phase CO_2 could indicate increasing storage security, but the specific mechanism cannot be uniquely determined from seismic data alone.

4.2.3 Electrical resistivity monitoring

Ketzin provided one of the strongest demonstrations of long-term ERT monitoring for geological CO_2 storage. Schmidt-Hattenberger et al. [9] demonstrated that permanent downhole electrodes could detect resistivity changes associated with replacement of conductive brine by resistive CO_2. Bergmann et al. [10] extended this approach using surface-downhole ERT, increasing spatial sensitivity around the storage interval. Subsequent studies [11–13] showed that the monitoring system remained stable over multiyear periods and that resistivity changes could be translated into estimates of CO_2 saturation when appropriately calibrated. Importantly, ERT-derived saturation estimates showed broad agreement with independent borehole logging results [13]. This provides strong evidence that electrical methods can contribute quantitative reservoir information rather than simply qualitative plume imaging.

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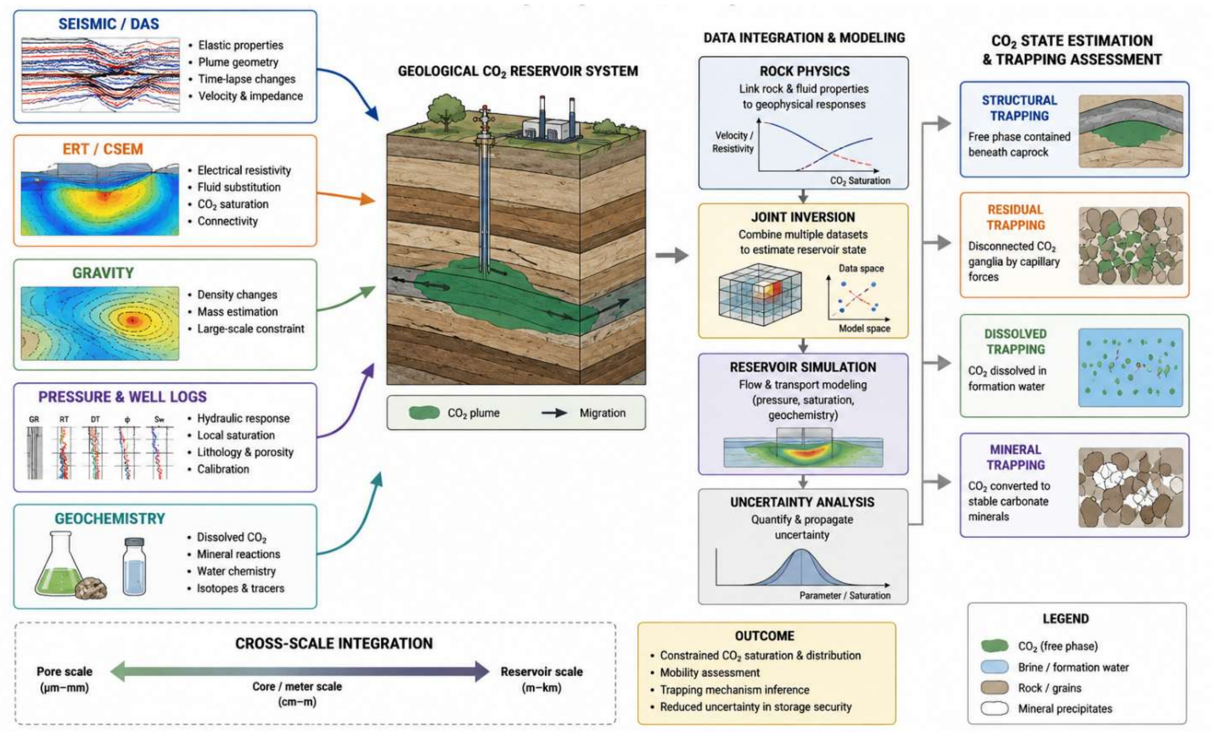

Figure 4.2. Integrated multiphysics framework for geological CO_2 monitoring, illustrating how seismic, electrical, gravity, borehole, pressure, and geochemical measurements can be combined through rock physics, joint inversion, reservoir simulation, and uncertainty analysis to constrain CO_2 saturation, mobility, and trapping state

4.2.4 Importance of multimethod integration

The Ketzin experience demonstrates why integrated monitoring is more informative than reliance on a single technique. Seismic methods provided higher spatial resolution and structural information, while ERT provided strong sensitivity to fluid replacement. Well logging supplied local calibration, and reservoir simulation helped interpret plume evolution. The strength of Ketzin therefore lies less in any single dataset and more in the consistency among independent observations.

4.3 Frio CO_2 Injection Experiment

The Frio brine pilot project in the United States was designed to investigate CO_2 injection into a saline sandstone reservoir under controlled field conditions. Compared with Sleipner and Ketzin, Frio involved a smaller injected volume but provided detailed borehole and geophysical measurements.

4.3.1 Time-lapse VSP observations

Al Hosni et al. [16] used time-lapse VSP data to examine changes in seismic velocity associated with CO_2 injection. A substantial reduction in P-wave velocity was observed near the injection zone. However, conventional Gassmann-based fluid substitution could not fully reproduce the measured change. This result is particularly important because it demonstrates that field-scale seismic response may be influenced by more than saturation alone. Potential contributing factors include:

- pressure changes;
- heterogeneous fluid distribution;
- patchy saturation;
- rock-fluid interactions;
- changes in effective stress.

Therefore, even high-quality borehole seismic observations may not support unique saturation estimation without additional physical constraints.

4.3.2 Importance for rock-physics calibration

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Frio highlights the value of field experiments in testing rock-physics assumptions. Models that perform well in laboratory conditions may not reproduce field-scale observations when heterogeneity, pressure, and geochemical interactions are introduced.

This is directly relevant to trapping-state monitoring because residual trapping and dissolution both modify fluid distribution at scales that may violate simple fluid-substitution assumptions.

4.4 Cross-Site Comparison of Major CO_2 Storage Projects

The five field sites differ substantially in geological setting, injection scale, monitoring design, and research objective. Their comparison therefore provides useful insight into the relative strengths of different geophysical approaches.

Table 4.1. Comparative summary of major CO_2 storage monitoring projects

Site	**Geological setting**	**Main monitoring methods**	**Primary geophysical achievement**	**Main trapping information**	**Major limitation**
Sleipner	Offshore saline aquifer	4D seismic, gravity	Reservoir-scale plume imaging	Strong evidence of stratigraphic trapping	Residual/dissolved fractions difficult to quantify
Ketzin	Onshore saline aquifer	Seismic, VSP, ERT, logging	Multimethod plume and saturation monitoring	Structural containment and post-injection stabilization	Trapping-state discrimination remains indirect
Frio	Saline sandstone	VSP, borehole methods	High-sensitivity velocity monitoring	Fluid-substitution response	Complex velocity-saturation relationship
Cranfield	Deep saline/CO_2 storage reservoir	Crosswell seismic, logging	High-resolution saturation characterization	Patchy fluid distribution	Limited interwell investigation volume
Otway	Onshore storage reservoir	4D seismic, DAS-VSP	Permanent high-repeatability monitoring	Dynamic plume evolution	Fiber sensitivity and inversion uncertainty

Several general trends emerge from this comparison: First, surface 4D seismic provides the best reservoir-scale spatial coverage. Second, crosswell and borehole techniques provide superior local resolution but limited spatial extent. Third, permanent ERT and DAS systems substantially improve temporal repeatability. Fourth, integrated datasets provide stronger constraints than individual methods. Finally, none of the sites demonstrates unambiguous geophysical partitioning of injected CO_2 among all four trapping mechanisms.

4.5 Integrated and Multiphysics Monitoring

A major conclusion from field experience is that complementary monitoring techniques should be interpreted jointly rather than independently.

Each geophysical method responds to different physical properties:

Different monitoring techniques provide complementary information because they respond to different physical and chemical properties of the CO2 storage system. Seismic methods are mostly sensitive to changes in the elastic properties of the reservoir caused by fluid substitution, pressure variation, and variation of effective stress. Electrical resistivity tomography (ERT) and electromagnetic

(EM) methods are mainly sensitive to changes in electrical conductivity resulting from the replacement of conductive formation brine by relatively resistive CO2. The gravity monitoring yields information about changes in the density and mass distribution in the subsurface, whereas the reservoir pressure measurements provide the hydraulic response to the CO2 injection and subsequent redistribution of pressure. Additional information on CO2 dissolution, changes in the chemistry of formation water and fluid-rock interactions that may ultimately lead to mineral trapping can be obtained from geochemical monitoring. The complementary sensitivities of these techniques are particularly useful since an anomaly detected by a single monitoring technique can have many possible explanations. For example, seismic velocity change could be due to increased CO2 saturation, a change in reservoir pressure or a change in fluid distribution. If the same reservoir volume also shows an increase in electrical resistivity consistent with brine displacement, then the interpretation of free-phase CO2 is more strongly constrained. Gravity measurements can give us additional information on density and mass redistribution, while pressure and geochemical observations allow us to separate hydraulic effects from changes associated with dissolution or fluid-rock reactions. The non-uniqueness of single monitoring methods can be overcome by joint interpretation of seismic, electrical, gravity, pressure and geochemical observations. Multiphysics monitoring provides multiple independent constraints on the evolving state of the reservoir, rather than a single physical property. This is particularly important to distinguish between CO2 plume detection and trapping-state characterization because no single geophysical measurement can uniquely identify all structural, residual, solubility and mineral trapping processes.

4.5.1 Seismic and gravity integration

Sleipner provides the clearest example. Seismic imaging constrains plume geometry, while gravity observations constrain density and mass [1–5]. If seismic data alone indicate a particular plume volume, different combinations of saturation and CO_2 density may reproduce the observed response. Gravity measurements restrict the allowable density distribution and therefore improve the estimate of stored CO_2 mass. The combination can be represented schematically as:

Seismic plume geometry + gravity mass constraint → improved saturation/density estimate

4.5.2 Geophysics and well logging

Well logging provides high-resolution but highly localized measurements. Pulsed-neutron logging, resistivity logging, sonic measurements, and saturation logs can therefore be used to calibrate broader geophysical datasets. At Cranfield and Ketzin, agreement between geophysical inversion and borehole observations increased confidence in saturation estimates [13,14].

4.5.3 Geophysics and geochemistry

Geochemical monitoring becomes increasingly important as CO_2 progresses toward dissolution and mineral trapping. A reduction in free-phase seismic response may suggest dissolution, but dissolved CO_2 is more directly constrained through fluid sampling and geochemical analysis. Similarly, mineral trapping cannot currently be verified uniquely from seismic or electrical observations alone. Mineralogical measurements and reactive-transport modeling therefore provide essential complementary information [29–33].

4.5.4 Integration with reservoir simulation

Reservoir simulation provides a physical framework linking injection history with expected plume migration and trapping.

A typical workflow is:

geological model → flow simulation → predicted saturation/pressure → rock-physics transformation → synthetic geophysical response → comparison with field data

If predicted and observed geophysical responses differ, the reservoir model can be updated. This process, often referred to as history matching or data assimilation, allows geophysical data to improve estimates of permeability, capillary pressure, heterogeneity, and plume distribution.

4.6 Joint Inversion and Reservoir-State Estimation

Joint inversion provides a more formal approach to integrating multiple geophysical datasets.
Consider a reservoir model (m) constrained by seismic data (d_s), electrical data (d_e), and gravity data (d_g). A combined objective function can be expressed conceptually as:

$$\Phi(m) = w_s\|d_s(obs) - d_s(cal)(m)\|^2 + w_e\|d_e(obs) - d_e$$

where (w_s), (w_e), and (w_g) are weighting terms, (R(m)) represents regularization, and (\lambda) controls the strength of the model constraint.
The objective is not simply to fit each dataset independently but to identify reservoir models that are simultaneously consistent with multiple physical observations.
Joint inversion is particularly attractive for CO_2 storage because many ambiguities are method specific.
For example:

- seismic may confuse pressure and saturation;
- electrical measurements may be affected by salinity;
- gravity may lack spatial resolution.

A model that simultaneously explains all three datasets is therefore more constrained.
However, joint inversion introduces additional challenges. Different datasets have different spatial resolutions, noise structures, acquisition geometries, and sensitivities. Appropriate weighting and cross-property relationships must therefore be defined carefully.

4.9 Can Current Geophysics Distinguish Trapping Mechanisms?

This question represents the central critical issue of the review. The field evidence demonstrates that detecting CO_2 is substantially easier than determining how it is trapped.

4.9.1 Structural and stratigraphic trapping

This mechanism can be identified with relatively high confidence when:

1. a free-phase CO_2 anomaly is imaged;
2. the anomaly is spatially associated with a known geological barrier;
3. repeated surveys demonstrate persistent confinement.

Sleipner provides the clearest example [1–3]. Thus, structural trapping has **high geophysical identifiability**.

4.9.2 Residual trapping

Residual trapping is more difficult because mobility depends on connectivity rather than saturation alone. A seismic or ERT inversion may indicate that 20% of the pore volume contains CO_2, but the measurement cannot directly establish whether the CO_2 forms one connected plume or many disconnected ganglia. Residual trapping therefore generally requires indirect inference from: drainage-imbibition history, stabilization of plume movement, capillary-pressure behavior, relative-permeability hysteresis, reservoir simulation, rock-physics sensitivity to patchiness. Geophysical identifiability is therefore **moderate**.

4.9.3 Solubility trapping

Solubility trapping is more difficult still.
A decrease in free-phase seismic response may indicate dissolution, but it may also reflect: plume spreading, reduced saturation, movement into unresolved thin layers, pressure equilibration, survey-resolution limitations. Geochemical observations and reservoir simulation are therefore normally required. Geophysical identifiability is **low to moderate**.

4.9.4 Mineral trapping

Mineral trapping remains the least directly identifiable mechanism. Changes in elastic or electrical properties caused by precipitation may theoretically be measurable, but the same changes can be produced by other processes. Consequently, geophysical observations must be integrated with mineralogical, geochemical, and reactive-transport

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evidence. Geophysical identifiability is currently low.

Table 4.2. Confidence in geophysical identification of different trapping mechanisms

Trapping mechanism	CO_2 detectability	Saturation quantification	Direct trapping-state identification	Main supporting information
Structural/stratigraphic	Very high	High	High	Geological structure + time-lapse imaging
Residual/capillary	High	Moderate–high	Moderate	Hysteresis + flow model + rock physics
Solubility	Low–moderate	Low	Low–moderate	Geochemistry + mass balance + simulation
Mineral	Very low	Very low	Low	Mineralogy + reactive modeling

The comparison illustrates a consistent pattern: **the geophysical response becomes less direct as CO_2 progresses toward more secure trapping states**.

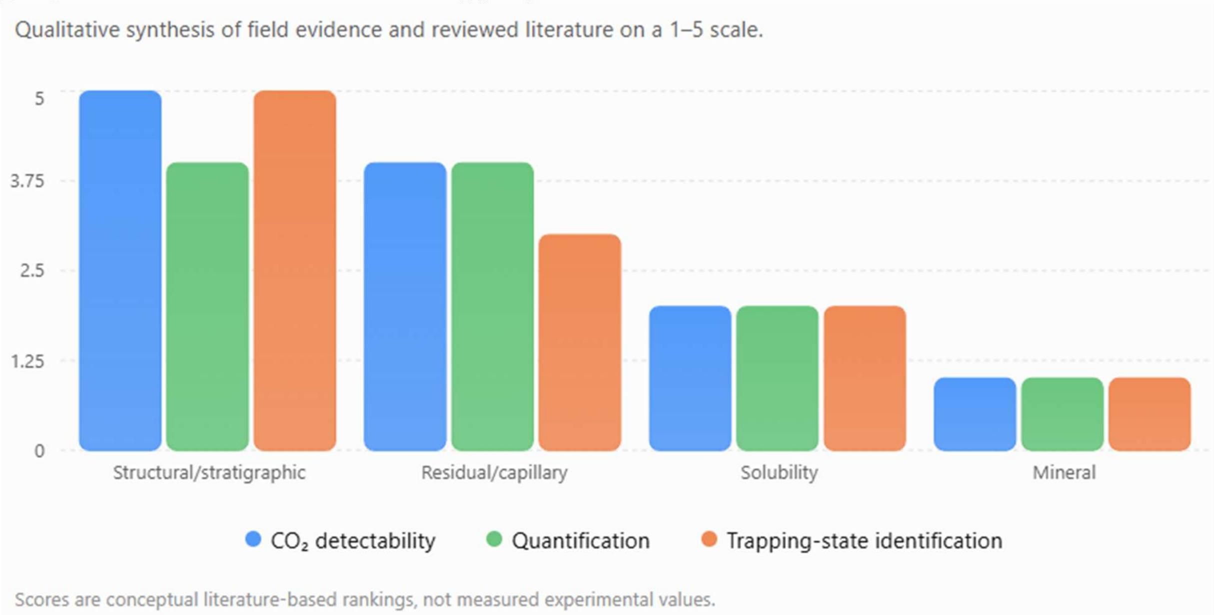

Figure 4.4. Qualitative comparison of CO_2 detectability, quantitative characterization capability, and trapping-state identifiability for the four principal geological trapping mechanisms. Rankings synthesize the literature reviewed in Chapters 2–4 and should not be interpreted as measured field-performance values.

4.10 Spatial and Temporal Resolution Limitations

Field monitoring is constrained by both spatial and temporal resolution.

4.10.1 Spatial scale

Residual trapping occurs at micrometer-to-millimeter pore scales, while surface seismic observations commonly represent effective properties over meter-to-decameter scales. This creates a scale gap of several orders of magnitude. Crosswell seismic and borehole methods partially reduce this gap but still cannot image individual disconnected CO_2 ganglia. Therefore, residual trapping must be inferred through upscaled rock-physics relationships rather than observed directly.

4.10.2 Temporal scale

Trapping processes occur over dramatically different timescales. Structural accumulation can develop during injection, whereas residual trapping may evolve over days to years. Dissolution can continue for decades or longer, and mineralization may operate over substantially longer periods depending on mineralogy. Conventional monitoring programs may not span the full duration required to observe all these processes. Permanent DAS, ERT, pressure sensors, and autonomous monitoring systems may therefore become increasingly important for long-term verification.

4.11 Proposed Integrated Monitoring Framework

Based on the combined field evidence, a robust future monitoring strategy should integrate observations across different physical sensitivities and spatial scales.

A proposed workflow is:

Step 1: Baseline characterization
3D seismic, well logs, pressure data, petrophysical analysis, mineralogy, and reservoir characterization establish the pre-injection state.

Step 2: Injection-phase monitoring
4D seismic, DAS/VSP, ERT, pressure measurements, and well logs track plume development and pressure evolution.

Step 3: Quantitative inversion
Seismic and electrical observations are converted into estimates of saturation and physical properties using calibrated rock-physics relationships.

Step 4: Multiphysics integration
Seismic, electrical, gravity, pressure, and geochemical datasets are interpreted jointly.

Step 5: Reservoir-model updating
Observed plume geometry and saturation are assimilated into reservoir-flow models.

Step 6: Trapping-state inference
The updated model is used to estimate the fractions of mobile, structurally trapped, residually trapped, and dissolved CO_2.

Step 7: Reactive-transport assessment
Geochemical and mineralogical observations are combined with reactive-transport simulations to assess mineral trapping.

Step 8: Long-term verification
Permanent or periodically repeated monitoring determines whether the plume remains stable and whether predicted trapping continues to increase.

The overall conceptual framework is:
Geological model → injection → geophysical observations → rock physics → inversion → reservoir simulation → trapping-state estimation → model update → verification

This approach recognizes that trapping mechanisms cannot generally be measured directly. Instead, they must be inferred from multiple observations constrained by physically realistic models.

4.12 Chapter Synthesis

The major field-scale CO_2 storage projects provide compelling evidence that geophysical techniques can successfully detect injected CO_2 and monitor plume evolution. Sleipner established the effectiveness of time-lapse seismic imaging and demonstrated strong stratigraphic control on plume development [1–3]. Gravity measurements added independent constraints on density and mass [4,5]. Ketzin demonstrated the advantages of multimethod monitoring through integration of seismic, VSP, ERT, well logging, and reservoir modeling [6–13]. The project also showed that permanent monitoring systems can provide stable multiyear datasets and support quantitative saturation estimation. Collectively, these projects show that structural and stratigraphic trapping can be identified with comparatively high confidence when CO_2 accumulations are clearly associated with geological barriers. Residual trapping is more difficult because geophysical techniques measure

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saturation rather than phase connectivity. Solubility trapping is generally inferred indirectly from changes in the free-phase plume together with geochemical and reservoir-model constraints. Mineral trapping remains primarily a geochemical and reactive-transport interpretation problem rather than a directly geophysical one. The field evidence therefore supports a fundamental conclusion: Resolving this limitation will require a shift from individual geophysical techniques toward integrated monitoring frameworks that combine seismic, electrical, electromagnetic, gravity, borehole, pressure, geochemical, and reservoir-simulation information.

The objective of future monitoring should therefore not be limited to producing increasingly detailed plume images. Instead, it should provide quantitative estimates of the evolving reservoir state, including CO_2 saturation, connectivity, mobility, dissolution, and mineralization. Achieving this transition from **plume monitoring to trapping-state verification** represents one of the most important remaining challenges in geological CO_2 storage research and forms the basis for the research gaps and future directions discussed in Chapter 5.

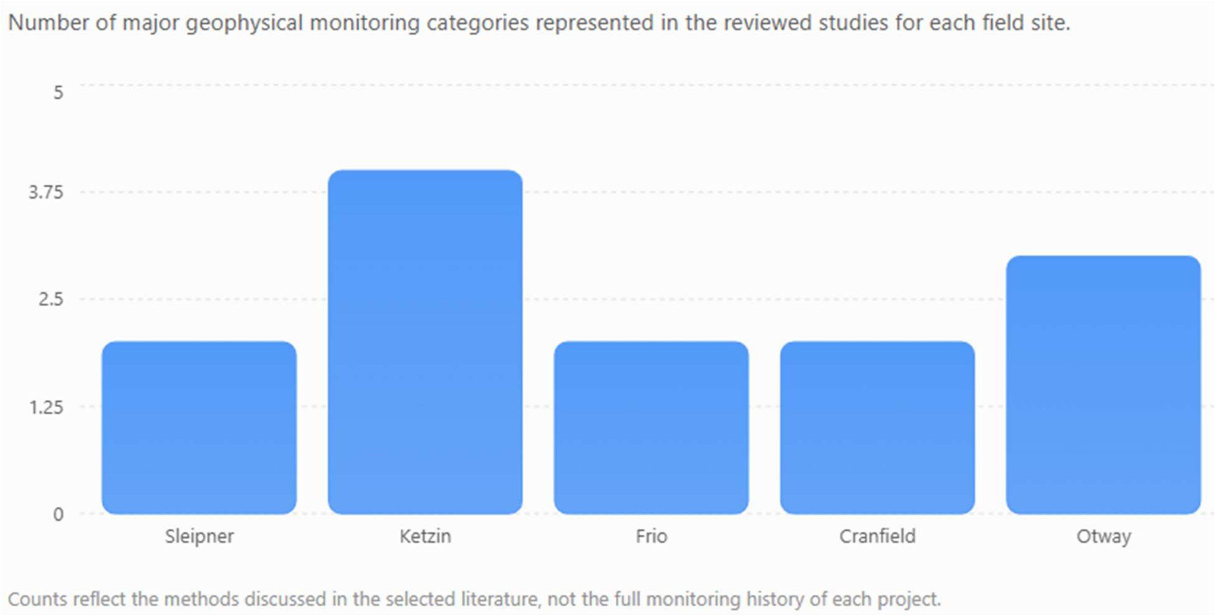

Figure 4.5. Diversity of major geophysical monitoring approaches represented in the reviewed literature for selected field-scale CO_2 storage projects. Ketzin provides the broadest multimethod example among the core studies considered here.

5. Research Gaps, Future Perspectives, and Conclusions

The literature reviewed in this study demonstrates that geophysical monitoring has become an established component of geological CO_2 storage. Field applications at Sleipner, Ketzin, Frio, Cranfield, and Otway have demonstrated that seismic, electrical, gravity, borehole, and fiber-optic techniques can detect injected CO_2 and characterize its spatial and temporal evolution [1–20]. Parallel advances in pore-scale imaging, capillary trapping studies, dissolution experiments, and reactive-transport modeling have substantially improved understanding of the physical and geochemical processes responsible for long-term CO_2 immobilization [21–35].

Despite these advances, an important gap remains between **detecting stored CO_2 and determining how it is trapped**. Existing geophysical techniques are highly effective for imaging free-phase CO_2 because replacement of brine produces substantial contrasts in elastic, electrical, and density properties. These contrasts become progressively weaker and less unique as CO_2 becomes residually immobilized, dissolves into formation water, or reacts to form stable minerals. Consequently, the mechanisms associated with increasing storage security are generally the mechanisms that are most difficult to verify directly through conventional geophysical observations.

Future research should therefore shift from conventional plume monitoring toward **quantitative trapping-state characterization**. This requires integration of rock physics, multiphysics geophysical monitoring, pore-to-reservoir-scale modeling, geochemistry, uncertainty quantification, and long-term field observations.

5.1 Major Research Gaps

5.1.1 From CO_2 saturation to CO_2 mobility

One of the most significant unresolved problems is the distinction between CO_2 saturation and CO_2 mobility. Most quantitative geophysical studies attempt to estimate CO_2 saturation from seismic velocity, reflection amplitude, electrical resistivity, or combinations of these properties [3,7,9–16]. However, saturation alone does not determine whether CO_2 is mobile.

For example, two reservoir volumes may both contain 20% CO_2 saturation. In one case, the CO_2 may form a connected phase capable of migration. In the other, it may occur as disconnected ganglia immobilized by capillary forces. These conditions have very different implications for storage security, although their effective seismic or electrical responses may not differ sufficiently for straightforward field-scale discrimination. Residual trapping studies demonstrate that connectivity depends on drainage-imbibition history, pore geometry, wettability, capillary pressure, heterogeneity, and saturation hysteresis [21–24,34]. Yet these parameters are rarely incorporated explicitly into conventional geophysical inversion.

The major research question should therefore evolve from:

“What is the CO_2 saturation?”

toward:

“What fraction of the detected CO_2 remains hydraulically connected and potentially mobile?”

Developing geophysical indicators of phase connectivity represents one of the most important future directions for trapping-state monitoring.

5.1.2 Scale gap between pore-scale trapping and field geophysics

Residual trapping originates at the pore scale, whereas conventional field geophysics measures effective properties over much larger volumes. At the pore scale, snap-off, ganglion formation, pore-throat geometry, contact angle, interfacial tension, and local capillary pressure determine whether CO_2 remains connected or becomes immobilized [21–24]. These processes occur at micrometer-to-millimeter scales. By contrast, surface seismic observations commonly represent effective properties over meter-scale or larger volumes. Even high-resolution crosswell seismic cannot directly resolve individual trapped CO_2 clusters.

This creates a fundamental multiscale problem:

Pore-scale trapping → core-scale effective properties → reservoir-scale saturation → geophysical response

Each transition requires upscaling.

Future research should therefore integrate micro-CT imaging, digital rock physics, pore-network modeling, laboratory ultrasonic and electrical measurements, reservoir simulation, and field geophysics. Such integration could establish more physically defensible relationships between pore-scale connectivity and measurable reservoir-scale properties.

5.1.3 Pressure-saturation separation

A second major challenge is distinguishing fluid-substitution effects from pressure-induced changes.

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During injection, both CO_2 saturation and reservoir pressure increase. Seismic velocity and impedance can respond to both processes. The Frio observations demonstrate that simple fluid-substitution models may not completely reproduce field-measured seismic changes [16]. This creates ambiguity because a seismic anomaly extending beyond the actual CO_2 plume may represent pressure propagation rather than fluid migration. Future monitoring strategies should therefore integrate seismic observations with direct pressure measurements and geomechanical models. Joint estimation of pressure and saturation would substantially improve quantitative interpretation and reduce the risk of incorrectly interpreting pressure-related anomalies as CO_2 migration.

5.1.4 Direct identification of residual trapping

Residual trapping is one of the most important mechanisms for immobilizing CO_2 after injection, but direct field-scale geophysical verification remains limited. Time-lapse monitoring can demonstrate plume stabilization, but stabilization alone does not prove capillary trapping. Structural confinement, dissolution, redistribution, or resolution limitations may produce similar observations. Potential future indicators of residual trapping may include:

- seismic attenuation and dispersion;
- frequency-dependent velocity;
- changes in electrical response associated with brine reconnection;
- hysteretic seismic behavior during drainage and imbibition;
- repeated pressure perturbation;
- integrated seismic-electrical signatures.

Research should therefore focus on whether the transition from connected to disconnected CO_2 produces reproducible geophysical signatures independent of average saturation.

5.2 Improving Detection of Solubility Trapping

Solubility trapping presents a fundamentally different monitoring challenge because the transition from free CO_2 to dissolved CO_2 reduces the strong fluid-property contrast that makes free-phase CO_2 geophysically visible.
Studies of convective dissolution demonstrate that CO_2 dissolution is controlled by diffusion, density-driven convection, permeability, geological heterogeneity, and fluid-fluid contact area [25–28,35]. However, most field geophysical methods do not directly measure dissolved CO_2 concentration. A reduction in seismic plume amplitude cannot automatically be interpreted as dissolution because it may also result from plume spreading, reduced saturation, migration into thin layers, or pressure equilibration. Future monitoring should therefore integrate:
Time-lapse geophysics + geochemical sampling + density constraints + reservoir simulation + mass balance.
Electrical and electromagnetic methods may also provide useful complementary information because dissolution modifies brine chemistry and potentially conductivity. However, salinity, temperature, clay conductivity, and other factors must be separated from the CO_2-related response. A particularly promising research direction is the development of coupled hydro-geophysical inversion in which dissolved CO_2 concentration is explicitly represented as a reservoir variable rather than inferred indirectly from disappearing free-phase saturation.

5.3 Challenges in Detecting Mineral Trapping

Mineral trapping represents the most permanent form of geological CO_2 immobilization but remains the most difficult mechanism to verify geophysically. Reactive-transport studies indicate that mineralization depends strongly on host-rock mineralogy, reactive surface area, temperature, pressure, fluid composition, reaction kinetics, and availability of Ca-, Mg-, and Fe-bearing minerals [29–33]. Mineral dissolution and precipitation may alter porosity, permeability, density, elastic stiffness, and electrical conductivity. In principle, these changes provide a basis for geophysical monitoring. The difficulty is that the expected changes are generally small and non-unique. An increase in seismic velocity could result from carbonate cementation but could also reflect pressure recovery, decreasing free CO_2 saturation, or mechanical compaction. Similarly, resistivity changes may result from mineral precipitation, salinity variation, saturation change, or temperature effects.

Future mineral-trapping verification should therefore combine geophysics with:

- fluid geochemistry;
- isotope measurements;
- mineralogical characterization;
- core and sidewall sampling where available;
- reactive-transport modeling;
- long-term seismic and electrical observations.

Rather than attempting to detect mineralization from one geophysical property, future studies should search for **consistent multiparameter signatures of fluid-rock reaction**.

5.4 Need for Trapping-Sensitive Rock-Physics Models

Conventional rock-physics models used in CO_2 monitoring primarily relate saturation to elastic properties. This approach has been highly successful for free-phase plume detection but is insufficient for trapping-state characterization. Future rock-physics models should incorporate not only saturation but also: CO_2 connectivity, patch size, capillary pressure, wettability. saturation history, pore geometry, pressure, frequency, mineral alteration. This represents a transition from **saturation-dependent rock physics** toward **trapping-sensitive rock physics**. For residual trapping, models should reproduce differences between drainage and imbibition at identical average saturation. For dissolved CO_2, models should quantify the comparatively subtle effects of changing brine composition. For mineral trapping, models should connect reaction-induced changes in pore structure and cementation to elastic and electrical properties. Laboratory experiments under reservoir pressure and temperature conditions will be essential for calibrating these relationships.

5.5 Multiphysics Monitoring as the Future Standard

The field evidence reviewed in Chapter 4 indicates that the most reliable interpretation is obtained when different physical measurements are combined.

No single geophysical method simultaneously provides optimal spatial resolution, temporal resolution, saturation sensitivity, mass sensitivity, and trapping-state information.

Table 5.1. Future role of different monitoring approaches in trapping-state characterization

Monitoring approach	Primary contribution	Future priority
4D seismic	Plume geometry and elastic changes	Quantitative pressure/saturation separation
DAS/VSP	High-repeatability seismic monitoring	Continuous plume and mobility surveillance
Crosswell seismic	High-resolution local characterization	Connectivity-sensitive rock physics
ERT	Brine displacement and saturation	Residual saturation monitoring
CSEM	Reservoir-scale resistivity	Integration with seismic
Gravity	Density and mass balance	Dissolution/mass constraints
Pressure monitoring	Hydraulic behavior	Separation of pressure and saturation

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Monitoring approach	Primary contribution	Future priority
Geochemistry	Dissolved/reacted CO_2	Solubility and mineral trapping
Digital rock physics	Pore-scale mechanisms	Connectivity-to-geophysics upscaling
Reservoir simulation	Process prediction	Trapping-fraction estimation

A future monitoring architecture should therefore combine complementary datasets according to storage-site characteristics rather than applying the same monitoring package universally.

5.6 Artificial Intelligence and Machine Learning

Machine learning has considerable potential for handling the large volumes of data expected from permanent monitoring systems. Leong et al. [20] demonstrated that deep-learning approaches can be trained to estimate CO_2 saturation distributions from time-lapse seismic observations. Similar approaches could potentially integrate seismic, ERT, pressure, gravity, and reservoir-simulation outputs. However, purely data-driven models face an important limitation: field datasets containing known trapping-state labels are extremely limited. A machine-learning model trained primarily on free-phase CO_2 examples cannot be expected to reliably identify residual, dissolved, or mineralized states that are poorly represented in the training dataset. Future research should therefore prioritize **physics-informed machine learning**. Physical constraints derived from multiphase flow, rock physics, capillary trapping, and geochemistry can be incorporated into model training and prediction. Machine learning should consequently be regarded as an acceleration and integration tool rather than a replacement for physical understanding.

5.7 Uncertainty-Aware Monitoring and Probabilistic Interpretation

Most storage-security questions cannot be answered responsibly using a single deterministic reservoir model.
Instead of reporting only one CO_2 saturation map, future monitoring studies should quantify the range of reservoir states consistent with the observations. For example, a monitoring result could state that available observations support a high probability of structural containment but only moderate confidence in the fraction of CO_2 that has become residually trapped. This type of probabilistic interpretation is particularly appropriate for trapping-state assessment because uncertainty increases from structural toward mineral trapping. Future monitoring frameworks should therefore explicitly quantify uncertainty associated with:

- geological architecture;
- petrophysical properties;
- rock-physics relationships;
- measurement noise;
- inversion;
- pressure-saturation separation;
- capillary hysteresis;
- geochemical reaction rates.

This would provide regulators and storage operators with more meaningful information than apparently precise but poorly constrained deterministic estimates.

5.8 Overall Conclusions

This review critically examined the ability of geophysical methods to detect and monitor the principal trapping mechanisms responsible for geological CO_2 storage. Evidence from field-scale monitoring, rock-physics studies, laboratory investigations, pore-scale analyses, and numerical simulations indicates that geophysical sensitivity differs substantially among structural, residual, solubility, and mineral trapping. Time-lapse seismic monitoring has demonstrated exceptional capability for detecting free-phase CO_2 and characterizing reservoir-scale plume migration. Sleipner provides perhaps the clearest demonstration, where repeated seismic observations successfully resolved stratigraphically controlled CO_2 accumulations [1–3]. Ketzin further demonstrated the advantages of combining seismic observations with permanent ERT, borehole measurements, and reservoir modeling [6–13]. Crosswell seismic at Cranfield showed that high-resolution velocity changes can support quantitative saturation estimation [14], while Frio demonstrated the complexity of converting field-scale seismic changes into saturation using simplified rock-physics models [16]. Otway illustrates the growing potential of permanent DAS systems for repeatable long-term monitoring [17,18]. Structural and stratigraphic trapping currently provide the highest confidence for geophysical identification because free-phase CO_2 generates strong physical-property contrasts and its accumulation can be related directly to geological barriers. Residual trapping represents a more difficult problem. Although residually trapped CO_2 remains detectable as a separate fluid phase, conventional geophysical methods are primarily sensitive to saturation rather than connectivity. Consequently, distinguishing mobile and capillary-immobilized CO_2 at similar saturation remains unresolved at field scale. Solubility trapping has still lower direct detectability because dissolution removes the strong contrast associated with free-phase CO_2. Geophysical evidence for dissolution is therefore generally indirect and requires integration with geochemistry, mass balance, and reservoir simulation [25–28,35]. Mineral trapping provides potentially the greatest long-term security but remains the least directly observable mechanism. Mineral reactions can modify reservoir physical properties, but these changes are generally subtle and non-unique. Geochemical and reactive-transport approaches therefore remain essential for mineral-trapping assessment [29–33].

The combined evidence reveals a fundamental monitoring paradox:

As CO_2 becomes progressively more securely trapped, it generally becomes more difficult to identify directly using conventional geophysical methods. This relationship should not be interpreted as a limitation that reduces the value of geophysics. Rather, it defines the next scientific challenge. Geophysical monitoring has successfully evolved from CO_2 detection toward plume imaging and quantitative saturation estimation. The next stage is to develop methods capable of characterizing **phase connectivity, mobility, dissolution, and mineralization**. Achieving this objective will require integration across spatial scales and scientific disciplines. Pore-scale trapping physics must be connected to rock-physics measurements, reservoir simulation, multiphysics geophysical observations, geochemistry, and uncertainty-aware inversion. Permanent monitoring technologies such as DAS and ERT, together with physics-informed machine learning, may further improve temporal resolution and reduce the cost of long-term verification. Ultimately, the future of geological CO_2 monitoring lies not in identifying a single geophysical technique capable of detecting every trapping mechanism, but in constructing integrated monitoring systems capable of combining multiple independent observations into physically defensible estimates of CO_2 state and mobility.

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