Monitoring CO_2 Dissolution and Mineralisation Using Inherent Isotope Tracers at the CarbFix2 Project, Iceland

Introduction

Geological carbon storage in basaltic formations has emerged as a promising strategy for permanent CO_2 removal due to the rapid conversion of dissolved CO_2 into stable carbonate minerals (Snæbjörnsdóttir et al., 2020). The CarbFix project in Iceland has demonstrated that CO_2 injected into reactive basalt can mineralise on timescales of months to years, rather than centuries (Matter et al., 2016; Snæbjörnsdóttir et al., 2020). This rapid mineralisation provides a high degree of storage security, but robust verification remains essential for regulatory compliance, carbon accounting, and public confidence of secure storage.

Conventional monitoring approaches at CarbFix have relied on the co-injection of artificial reactive and non-reactive tracers to quantify dissolution and mineral trapping. While effective, such tracers add operational complexity and cost (Holdsworth et al., 2026). Here, we present an alternative approach of using the inherent isotope tracers naturally present in the injected CO_2 stream. Specifically, $\delta^{13}C$ of CO_2 is used as a reactive tracer, while ^3He serves as a conservative, non-reactive tracer. By combining these two isotopic systems, it is possible to distinguish mixing processes from mineralisation and therefore quantify the proportion of CO_2 dissolved and permanently stored.

Method Background

Carbon Isotope Fractionation During Mineralisation

Carbonate mineral formation from dissolved CO_2 causes isotopic fractionation. The lighter isotope, ^{12}C, is preferentially incorporated into solid carbonate phases, leaving the residual dissolved CO_2 enriched in ^{13}C. This isotopic partitioning results in an increase in $\delta^{13}C$ values in the remaining CO_2 phase as mineralisation progresses. If progressive mineral precipitation occurs in a closed or semi-closed system, the isotopic evolution of the remaining CO_2 follows a Rayleigh-type fractionation trend. Thus, increasing $\delta^{13}C$ values provide a direct indicator of reactive carbon removal from solution.

Helium-3 as a Conservative Tracer

Helium-3 (^3He) is chemically inert and does not participate in aqueous or mineral reactions under subsurface conditions. Its concentration therefore changes only due to physical processes such as dilution or mixing. When CO_2 and ^3He are transported together in injected fluids, any preferential removal of CO_2 relative to ^3He indicates reactive loss (i.e. removal from solution by mineralisation) The ratio $CO_2/^3He$ thus provides a measure of reactive depletion, while $\delta^{13}C$ constrains isotopic fractionation. Together, these parameters allow discrimination between: (i) Pure mixing with background fluids; (ii) Dissolution without mineral precipitation; (iii) Mineralisation; and (iv) Combined mixing and mineralisation.

Mineralisation Trend

Figure 1 illustrates the conceptual evolution of $CO_2/^3He$ versus $\delta^{13}C$ during progressive mineralisation. As carbonate precipitation proceeds the $CO_2/^3He$ decreases due to removal of carbon into solid phases and $\delta^{13}C$ increases due to preferential incorporation of ^{12}C into carbonate minerals. This produces a trajectory of decreasing $CO_2/^3He$ accompanied by isotopic enrichment.

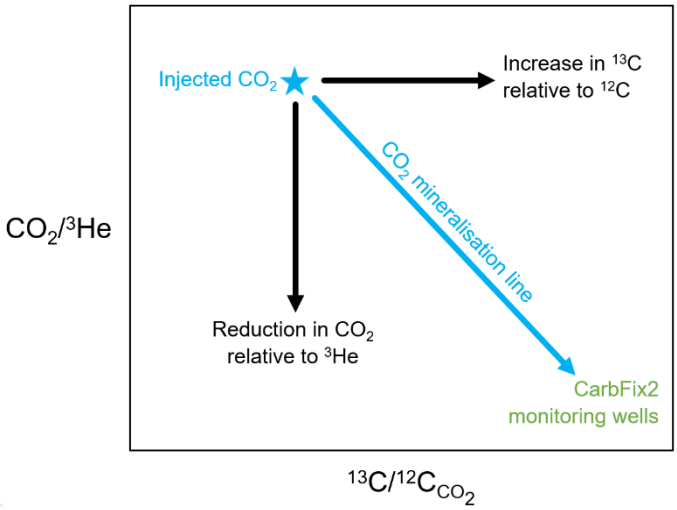

Figure 1 *Conceptual relationship between $\delta^{13}C$ and $CO_2/^3He$ during progressive mineralisation (from Holdsworth et al., 2025). Increasing $\delta^{13}C$ values correspond to preferential removal of ^{12}C into carbonate minerals, while declining $CO_2/^3He$ reflects reactive CO_2 loss relative to conservative ^3He.*

Application to the CarbFix2 System

Site Context

At CarbFix2, CO_2 derived from geothermal emissions is dissolved in water prior to injection into basaltic formations at temperatures up to ~265°C. Upon injection, dissolved CO_2 reacts with divalent cations released from basalt dissolution, forming carbonate minerals such as calcite, magnesite, and siderite (Matter et al., 2016). A 2014 tracer test indicated that only 3–25% of injected fluids reached the monitoring wells, demonstrating substantial mixing and dispersion (Ratouis et al., 2022). This highlights the necessity of distinguishing dilution from mineralisation.

Proof of Concept: Capture Tower (2018)

The inherent tracer approach was first tested on injection fluids from the CarbFix2 capture tower (Figure 2). Analysis revealed a systematic decrease in $CO_2/^3He$ accompanied by increasing $\delta^{13}C$ values, consistent with progressive dissolution and reactive carbon loss. Quantitative modelling indicated that 51 ± 10% of injected CO_2 dissolved within the tower system prior to subsurface injection. This result demonstrated that inherent isotopes can successfully quantify dissolution without artificial tracers.

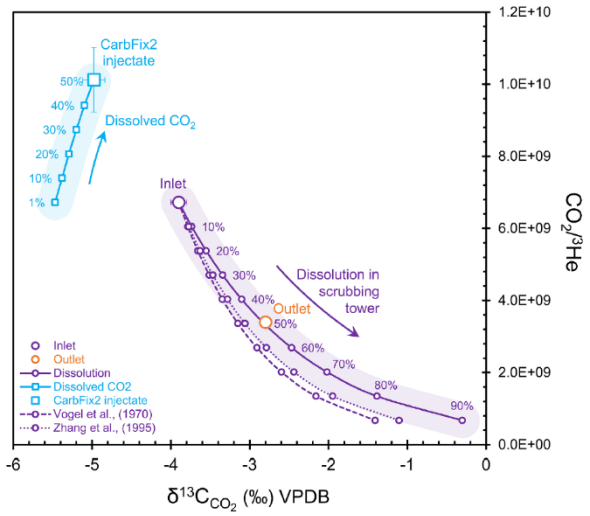

Figure 2 *Plot of $CO_2/^3He$ against $^{13}C/^{12}C$, with the measured value of the gas inlet and modelled dissolution lines shown as CO_2 dissolves. Measurement of the gas outlet shows that 51 ± 10% of the CO_2 is dissolved in the scrubbing tower (from Holdsworth et al., 2026).*

Mixing Versus Mixing + Mineralisation

Mixing between injected fluids and background geothermal waters produces dilution trends. In such cases: $CO_2/^3He$ decreases proportionally, $\delta^{13}C$ shifts modestly toward background values, and no strong fractionation trend develops. Figure 3 contrasts a mixing-only scenario with a combined mixing +

mineralisation model. Field data from CarbFix monitoring wells fall below the mixing-only trend, indicating additional CO_2 loss beyond dilution.

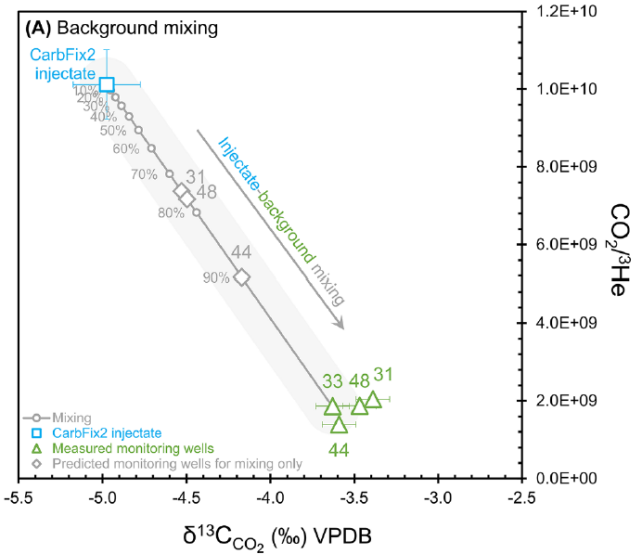

Figure 3 *Plot of $CO_2/^3He$ against $^{13}C/^{12}C$ depicting the modelled injectate-background mixing line, plotted using Well HE-33 as a background. Using this line, we can model where the measured monitoring wells would plot if mixing was the only process causing the loss of CO_2. It is clear that the monitoring wells plot below where they would do if only mixing was occurring in the reservoir (from Holdsworth et al., 2026).*

Monitoring Well Observations

Comparison of the inherent tracer composition of the injected dissolved CO_2 with the monitoring well samples illustrated that the monitoring wells exhibited lower $CO_2/^3He$ ratios than predicted by mixing alone, along with enrichment in $\delta^{13}C$ consistent with isotopic fractionation and data plotting below the theoretical mixing line. A combined model incorporating both mixing and mineralisation reproduced the observed data. Estimated mineralisation magnitudes were consistent with previous tracer-based studies (Clark et al., 2020; Gunnarsson et al., 2018). These findings indicate that CO_2 loss relative to ^3He cannot be explained by dilution alone and requires carbonate precipitation.

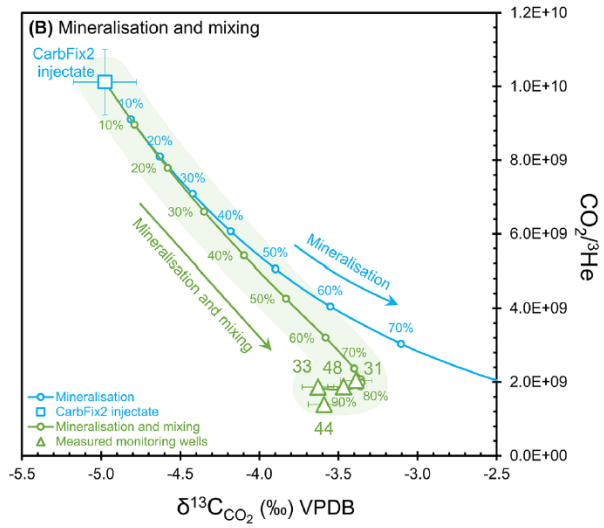

Figure 4 *Plot of $CO_2/^3He$ against $^{13}C/^{12}C$ showing that combining CO_2 mineralisation and mixing can explain the data and indicates that over 60% of the injected CO_2 is being mineralised in the subsurface. (from Holdsworth et al., 2026). This matches the estimate of the extent of mineralisation from previous work of Clark et al., in 2020.*

Advantages and Limitations of the Method

The advantages of this approach are that it reduces the need for injection of artificial tracers by leveraging naturally occurring isotopic signals. It enables quantification of both dissolution and mineral trapping processes, while remaining cost-effective and scalable for broader deployment. In addition, it is compatible with long-term monitoring frameworks, making it well suited for sustained observation over long time periods.

The limitations of deploying the method at Carbfix are that the injected CO_2 originates from the same geothermal system as background fluids, resulting in similar inherent isotopic signatures. This reduces isotopic contrast and analytical sensitivity. The method would likely be more powerful in systems where injected CO_2 originates from isotopically distinct industrial or biogenic sources.

Conclusions

This study demonstrates that inherent isotope tracers, with $\delta^{13}C$ as a reactive tracer and ^{3}He as a conservative tracer, can effectively quantify CO_2 dissolution and mineralisation in basalt-hosted carbon storage systems. Our findings indicate that approximately 51 ± 10% dissolution was quantified in the capture tower. Data from the monitoring wells show that mineralisation is required in addition to simple mixing to explain the observed signals. The estimated magnitude of mineralisation is consistent with results from independent tracer studies, and the inherent tracer method offers a scalable alternative to artificial tracer injection. Hence, the inherent isotope approach offers a robust verification framework for permanent CO_2 mineral storage and strengthens monitoring capabilities for rapid basalt carbonation systems.

Acknowledgements

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