Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Volume 2

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First edition 2005

Library of Congress Cataloging in Publication Data
A catalog record is available from the Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record is available from the British Library.

ISBN: 0-08-044570-5 (2 volume set)

Volume 1: Chapters 8, 9, 13, 14, 16, 17, 18, 24 and 32 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. EU co-funded work appears in chapters 19, 20, 21, 22, 23, 33, 34, 35, 36 and 37. Norwegian Research Council (Klimatek) co-funded work appears in chapters 1, 5, 7, 10, 12, 15 and 32.

Volume 2: The Storage Preface, Storage Integrity Preface, Monitoring and Verification Preface, Risk Assessment Preface and Chapters 1, 4, 6, 8, 13, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. Norwegian Research Council (Klimatek) co-funded work appears in chapters 9, 15 and 16.

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Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 2
D.C. Thomas and S.M. Benson (Eds.)

Chapter 3

NATURAL CO_2 FIELDS AS ANALOGS FOR GEOLOGIC CO_2 STORAGE

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ABSTRACT

Our study evaluated three underground gas fields in the USA that have been effective CO_2 traps for millions of years: the Jackson, McElmo, and St. Johns Domes. Together, these fields stored 2.4 billion t of CO_2, equivalent to more than 1 year of USA power plant emissions. Because CO_2 in these fields has been commercially extracted for industrial uses, the fields offer data on natural CO_2 reservoirs, cap rocks, and production operations. M0cElmo Dome, the largest and most important field, originally stored 1.6 billion t of supercritical CO_2 within a carboniferous carbonate reservoir at a depth of 2300 m. Carbon isotope data indicate the CO_2 originated from a nearby igneous intrusion dated to 70 Ma. Its cap rock is a 400-m thick sequence of salt (halite), which is finely layered and unperturbed by faults which cut the underlying reservoir; there is no evidence of CO_2 leaking into the overlying strata. McElmo Dome has two decades of safe operational history. It currently produces 15 million t/year (800 MMcfd) of 99%-pure CO_2, which is transported 900 km via pipeline to depleted oil fields for re-injection and enhanced recovery. However, the three fields in our study represent a small sampling of geologic situations, insufficient for defining universal criteria for cap rock integrity. Building scientific and public acceptance for geologic CO_2 storage may be facilitated if proposed projects each had a local or regional natural analog.

INTRODUCTION

Geologic storage has been proposed as a promising option for reducing net emissions of CO_2. But is geologic storage a safe and long-term disposal option? Since the early 1980s, in the USA and several other countries, CO_2 has been injected on a large scale into depleted oil fields for enhanced oil recovery (EOR). The safety record of this activity has been excellent and industry's two decades of experience with EOR represents an invaluable tool for assessing the near-term performance of geologic storage projects [1].

However, the long-term safety and performance of geologic storage is still unknown. This effectiveness still must be quantified to demonstrate storage feasibility as well as to win public acceptance [2]. One approach is to numerically simulate the flow and storage of CO_2 in candidate storage sites. This approach requires an extremely large data set on reservoir properties, as well as upgrading simulation codes to better model long-term geochemical reactions, but is only feasible at well-documented depleted oil and gas fields [3,4].

A parallel empirical approach, taken by this and several other studies, is to examine sites where large volumes of nearly pure CO_2 have naturally accumulated and have been stored in geologic formations over a demonstrably long time period (millions of years). These naturally occurring CO_2 deposits provide unique natural analogs for evaluating the long-term safety and efficacy of storing anthropogenic CO_2 in geologic formations. CO_2 has been trapped for millions of years in reservoirs with effective cap rocks, such as thick salt or shale deposits. In other settings, CO_2 springs and fluxes developed where cap rocks were breached or faulted. Understanding why certain natural geologic settings are effective CO_2 traps while others are not can help guide the screening and designing of engineered sites for CO_2 storage. Production operations at CO_2 fields also provide proven and low-cost technologies applicable to engineered geologic storage sites. These natural analogs offer unique natural laboratories for studying the long-term storage of

CO_2 underground and can help in the screening of candidate sites for geologic storage. Natural analogs in the Colorado Plateau (USA), Europe, and Australia are currently undergoing study in separate research projects [5–7].

Our study focused on three commercial CO_2 fields in the USA. The petroleum industry has been exploiting natural CO_2 fields for over two decades, yet little technical information has been published about this activity [8]. Our study had three objectives that are consistent with CCP's goals of understanding geologic storage and developing long-term, cost-effective verification and monitoring technologies:

- *Establish CO_2 storage as a natural process*. Studying natural analogs documents that CO_2 storage in geologic formations is indeed a natural process in many geologic settings.
- *Document long-term impacts of CO_2 storage*. More convincingly than any model or laboratory experiment, natural analogs can demonstrate empirically the long-term chemical and physical interactions of CO_2 with reservoir rocks and fluids. Dating the emplacement of non-leaking CO_2 deposits can uniquely establish the integrity of geologic storage over very long time periods (thousands to millions of years).
- *Assess surface and subsurface CO_2 handling technologies*. Many of the production, monitoring, and safety techniques and facilities developed by the commercial CO_2 production industry can be adapted for long-term geologic storage of CO_2. These technologies and their costs have never been comprehensively documented.

METHODOLOGY

To conduct this study, we assembled geologic and engineering data from each of the three fields into a geographic information system database for mapping and analysis. We also conducted gas sampling and analyzed molecular composition, as well as stable and noble gas isotopes. Figure 1 shows the location of the three fields, while Table 1 provides a summary of each site's characteristics. This section discusses the key aspects of our study, including: geologic setting; CO_2 origin, timing, and storage; cap rock integrity; production operations; and implications for geologic storage for each of the three natural analog fields.

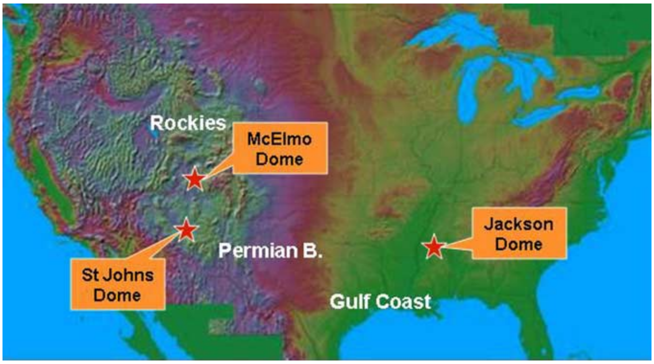


Figure 1: Location map of the three CO_2 fields.

RESULTS AND DISCUSSION

Geologic Setting

St. Johns Dome

The St. Johns Dome is a large (1800 km^2), asymmetrical, faulted anticline located on the southern part of the Colorado Plateau in east-central Arizona and west-central New Mexico [9]. CO_2 is trapped within

TABLE 1
SUMMARY OF NATURAL CO_2 FIELD STUDY SITE CHARACTERISTICS

Field	**State**	**Operator**	**Original CO_2 in place**		**2003 CO_2 production**		**Reservoir lithology**	**Depth (m)**	**Cap rock**	**Years stored**
			10^6 t	**Tcf**	**10^6 t/year**	**MMcfd**				
St. Johns	AZ	Ridgeway	730	14	0.02	1	Sandstone	500	Anhydrite	0–6 Ma?
Jackson Dome	MS	Denbury Resources	100	2	3.5	185	Sandstone Some carb	4700	Carbonate	70 Ma?
McElmo Dome	CO	Kinder Morgan	1600	30	15	800	Carbonate	2300	400 m salt	70 Ma?
All 3			2430	46	18.5	986				

sandstones of the Permian Supai Formation. Overlying and intercalated evaporite deposits (anhydrite, gypsum) and shales act as cap rocks and local seals (Figure 2). The Supai Formation thins over the dome, concordant with the structure, demonstrating that the dome began as an older (280 Ma) basement structure which later intensified during the Laramide Orogeny (Cretaceous, 65 Ma). The St. Johns field is 30 km northeast of the Springerville Volcanic Field (SVF), a large Plio-Pleistocene (0.3–5 Ma) igneous feature, but we have no data directly linking the two.

Jackson Dome

The Jackson Dome is an igneous intrusion of Late Cretaceous age (70 Ma) located in central Mississippi. Numerous CO_2 deposits occur on the eastern flank of this structure. The largest is the Pisgah Dome CO_2 field, a symmetrical, faulted anticline located in the onshore Gulf of Mexico province [10]. CO_2 is trapped within sandstone and carbonate reservoirs of the Jurassic Buckner, Smackover, and Norphlet Formations by structural closure and permeability barriers.

McElmo Dome

The McElmo Dome is a large (800 km^2) anticline located on the Colorado Plateau in southwestern Colorado. CO_2 is trapped within the Carboniferous (Mississippian) Leadville Limestone [11]. McElmo Dome is only a few km north of the Sleeping Ute Mountain laccolith, a large dacitic igneous intrusion dated at 70 Ma, which may be the source of the CO_2 deposit, as discussed below.

CO_2 Storage

As part of this project we sampled CO_2 production wells at each of the three study fields and analyzed the gases for major chemical composition and stable carbon isotopes. Although additional noble gas analyses are underway, early results are presented here.

St. Johns Dome

The Supai Formation contains an estimated 730 million t (13.9 Tcf) of CO_2 which, due to its relatively shallow depth (300–750 m), is stored in a free gas state. The field's reservoir architecture is complex, with multiple, vertically dispersed reservoirs consisting of sandstone, siltstone, and vuggy dolomite (porosity 11–20%, permeability 0.5 to >100 mD) that are separated by thin, impermeable anhydrite seals ($k < 0.010.25$mD). CO_2 concentrations vary from 83 to 99%, averaging 92%. Other constituents include nitrogen (N_2: 6.6%), argon (Ar: 0.2%), and commercially significant quantities of helium (He: 0.6%).

Jackson Dome

The Pisgah anticline originally contained an estimated 100 million t (2 Tcf) of CO_2, making it the smallest of the three study sites. With a reservoir depth of about 4700 m, the CO_2 is stored in the supercritical state. Its reservoir architecture is complex, with fluvial and eolian sandstones with 8–15% porosity and up to 1 D

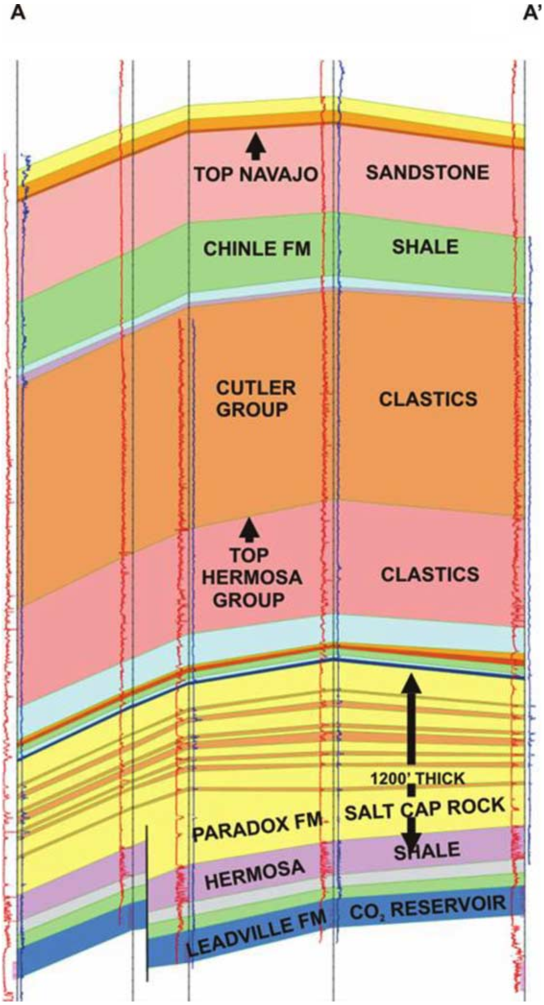


Figure 2: Structural cross-section of the CO_2 reservoir and cap rock at McElmo Dome.

permeability. The CO_2 concentration averages 99%, with minor methane (CH_4), N_2 and significant hydrogen sulfide (H_2S) of up to 1%.

McElmo Dome

The Leadville Formation originally contained 1.6 billion t (30 Tcf) of CO_2 stored in a supercritical state at a depth of 2300 m. Reservoir architecture is complex, with interbedded dolomite (porous, permeable) and limestone (impermeable) capped by an erosional unconformity. The reservoir porosity averages 11% and permeability 20 mD. The CO_2 concentration of this deposit ranges from 96 to 98%, along with minor N_2 (1.6–2.2%), CH_4 (0.2–0.9%), and H_2S (0–15 ppm). Traps are provided by structural closure, permeability barriers in the Leadville, the water/CO_2 contact, and a 400-m thick salt cap rock; faults in the Leadville die out in the lower portion of this salt cap rock.

CO_2 Origin

St. Johns Dome

$\delta^{13}CO_2$ values within the gas were uniform at the three wells we sampled across the St. Johns field (-3.8‰), suggesting that the CO_2 was generated from a single source or well-mixed multiple sources and that internal barriers and compartmentalization are minimal. Major gas composition within the reservoir exhibits significant reverse gravity segregation, with heavier CO_2 concentrated at the crest and lighter He and N_2 more prevalent on the northern flank. There are two possible explanations. The more likely is that CO_2 and He are continuously emanating from beneath the halite–anhydrite boundary at the southeastern edge of the nearby Holbrook salt basin, entering the northwest portion of St. Johns Dome. This origin is supported by heat flow distribution, which is low over the salt basin and high (>100 mW/m^2) over the St. Johns field, suggesting convective flow. Another possible explanation for the geochemical trends is that the lighter (and smaller) He and N_2 components have preferentially escaped from the crest of the structure, leaving behind extremely pure (99%) CO_2. This is less likely given that all wells sampled have similar overburden thickness (500 m), so the flank wells should be just as likely to leak (or not leak) He as the crest. The SVF is another potential CO_2 source, but we have not yet found evidence of a direct connection with St. Johns Dome, as there appears to be with the Holbrook salt basin.

Jackson Dome

$\delta^{13}CO_2$ values from gas sampled in 10 wells range from -3.55 to -2.57‰. The $^3He/^4He$ ratio ranged from 4.27 to 5.01 Ra, indicating strong mantle signature. The $^4He/^{40}Ar$ ratios range from 1.26 to 2.52, also indicative of mantle origin. These noble gas isotope data demonstrate that the CO_2 at Pisgah Dome was outgassed from the mantle, rather than derived from thermal decomposition of carbonate [12]. The most likely source was the Jackson Dome intrusion.

McElmo Dome

$\delta^{13}CO_2$ from gas sampled at 28 wells within the field are quite uniform (-4.3 to -4.5‰), demonstrating no significant internal flow barriers or compartments. However, a subtle gradation is apparent, emanating away from the Ute Mountain laccolith. The CO_2 likely formed by direct outgassing from Ute Mountain rather than thermal decomposition of the Leadville Limestone (which has $\delta^{13}CO_2$ value of -0.64‰). Our noble gas analysis in progress may help to resolve this uncertainty.

CO_2 Timing

St. Johns Dome

Noble gas analysis currently underway is the best hope for resolving the origin and timing of CO_2 emplacement at St. Johns Dome. Our geologic mapping suggests that the earliest likely storage of CO_2 was immediately following the Laramide Orogeny (65 Ma) that generated the current structural closure. Given the thinning of the Supai Formation over the dome, it is even possible that a modest structural closure existed as early as during the Permian (280 Ma). On the other hand, there is no data establishing the most recent possible time of CO_2 emplacement. CO_2 and other gases could even be continuing to fill the St. Johns Dome, overspilling the structure and charging the overlying Glorieta Sandstone and San Andres Limestone, without necessarily leaking through the cap rock.

Jackson Dome

Our noble gas data, previously cited, suggest that timing was coeval with the Jackson Dome intrusion, which is dated to about 70 Ma.

McElmo Dome

Under either CO_2 origin scenario (outgassing or decomposition), the nearby Ute Mountain laccolith (70 Ma) is the most likely source for CO_2 emplacement at McElmo Dome.

Cap Rock Integrity

St. Johns Dome

The multiple but thin, mainly anhydrite cap rocks at St. Johns Dome—while a reasonably good seal for preserving commercial quantities of CO_2 and He—may not form as thorough a long-term seal as the thicker halite cap rocks at McElmo and Jackson Domes. Four wells at the field encountered voids (karsts?) or lost circulation while drilling through the San Andres Formation and had to be abandoned. CO_2 is widely present (in non-commercial quantities) in the overlying Permian Glorieta Sandstone and San Andres Limestone, entering these formations either by gradual seepage through the cap rock matrix porosity, or by overspill and lateral migration, or migration along fault planes. On the other hand, the presence of He, a light and small molecule particularly prone to leakage, in high concentrations (up to 1.1%) indicates that the cap rock seals over the north flank of the field. But the low He concentration (0.1%) at the crest of the structure, the reverse expected under gravity segregation, suggests that it and N_2 may have preferentially leaked through the cap rock, leaving behind nearly pure (99%) CO_2. Detailed sampling and analysis of noble gases in the reservoir, along with soil gas analysis above the field, is needed to fully evaluate cap rock integrity.

Jackson Dome

Sudden geopressuring with depth—50% higher than the hydrostatic gradient—strongly suggests that the Bruckner Carbonate is an excellent cap rock seal to underlying CO_2 reservoirs. However, this cap rock has not been cored, usually is not fully logged, and thus remains poorly characterized.

McElmo Dome

The 400-m thick halite unit above the Leadville CO_2 reservoir apparently has acted as an excellent cap rock for millions of years. There is no significant evidence of CO_2 locally above the Leadville or in the ground water. Faults that cut the Leadville die out in the lower portion of this salt layer, as indicated by thinly layered shales within the salt unit that are unaffected by faulting (Figure 2). However, detailed sampling and analysis of noble gases in the reservoir, along with soil gas analysis above the field, is needed to fully evaluate cap rock integrity.

CO_2 Production Operations

This section is based on internal company documents and operating procedures discussed in Ref. [13] or not previously documented.

St. Johns Dome

Ridgeway Petroleum Corp., the field operator, has drilled 21 CO_2 production wells since discovering the field in 1994. At present, due to limited local market demand and lack of a CO_2 pipeline, only one well is on line producing approximately 50 t/day (1 MMcfd). The production wells were drilled with air or with a fresh water and starch-based mud to avoid formation damage and were completed in one or more of the three CO_2-bearing zones (Ft. Apache, Amos Wash, and Upper Abo/Granite Wash) at an average depth of 850 m. The wells were completed using 11.4-cm diameter casing, consisting of amine carbon gauze fiberglass or conventional carbon steel lined with high-density polyethylene (HDPE) to minimize corrosion. The St. Johns wells were considerably less expensive to drill and complete ($300,000) than the deeper wells at McElmo and Jackson Domes, making them good analogs for shallow geologic storage projects. Since discovery in 1994, CO_2 exploration and production activities at the field have been accident free. Given the extremely low population density at the field (<0.1 residents/km^2), impacts on the natural and human environment have been negligible.

Jackson Dome

Field operator Denbury Resources Inc. currently produces about 3.5 million t/year (185 MMcfd) of CO_2. Production wells, on 2.6 km^2 spacing, are equipped with up to 10,000-psi working pressure wellheads, which can be operated remotely by a control station (Figure 3). Stainless steel is used for the production casing and downhole fittings, the high-pressure wellheads, and surface flow lines to the central facility. Production costs (including depreciation and amortization) average about $0.007 m^{-3} ($0.20 Mcf^{-1}). Produced CO_2 is dehydrated (<0.27 kg H_2O/tCO_2), compressed, and transported to EOR fields via a 293-km, 50-cm diameter carbon steel pipeline with no internal protective coating. It is maintained at a supercritical state at all times to preclude hydrate formation.

McElmo Dome

Shell, the original field operator, and current operator Kinder Morgan have drilled a total of 60 CO_2 production wells since 1976. Currently the field produces 15 million t/year (800 MMcfd) of CO_2 from 41 wells. Early wells were completed using perforated carbon steel casing across the Leadville production zone, with high-chromium steel (13% Cr) production tubing to convey CO_2 to the surface. Recent wells

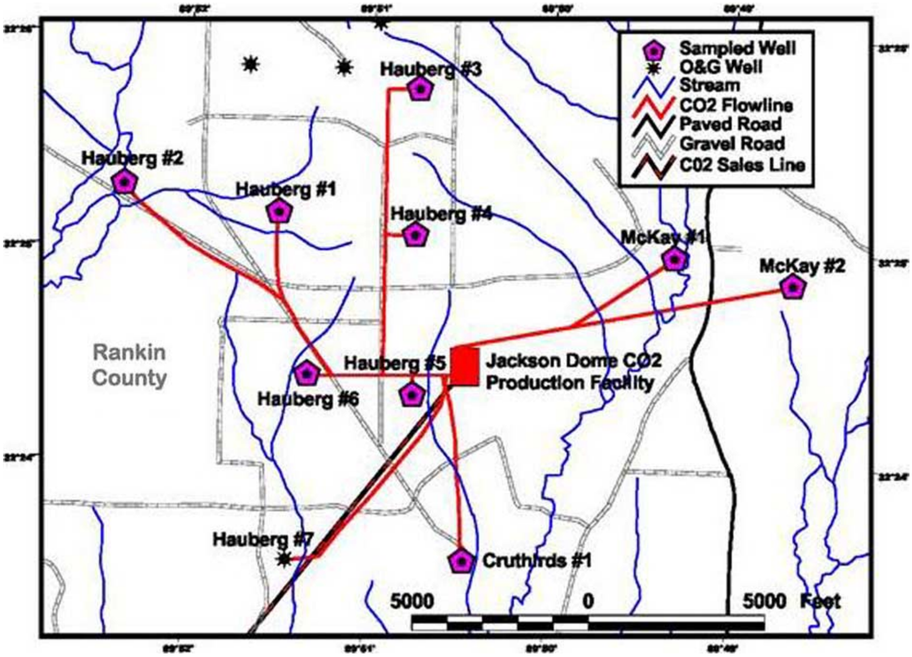


Figure 3: CO_2 gathering system at the Pisgah field, Jackson Dome.

employ tubingless completions using 17.8-cm chromium steel casing to increase per-well production (up to 1600 t/day) while lowering cost. A field-wide supervisory control and data acquisition (SCADA) system provides communications and control of the facilities from the Cortez field office, including capability to remotely open/close wellhead and cluster shutdown valves, compressors, and the central facilities. Processing facilities reduce water content of produced gas to < 0.09 kg H_2O/tCO_2 (10 lb/MMscf). The dry CO_2 is compressed to 14.5 MPa (2100 psi) in two-stage, electrically driven compressors. The dry, supercritical CO_2 is cooled to 16–38 °C and then transported via the 800-km, 76-cm carbon steel Cortez pipeline to EOR projects in the Permian basin. Since commercial production began in 1983, over 235 million t (4.2 Tcf) of CO_2 has been produced with no safety or environmental incidents (Figure 4).

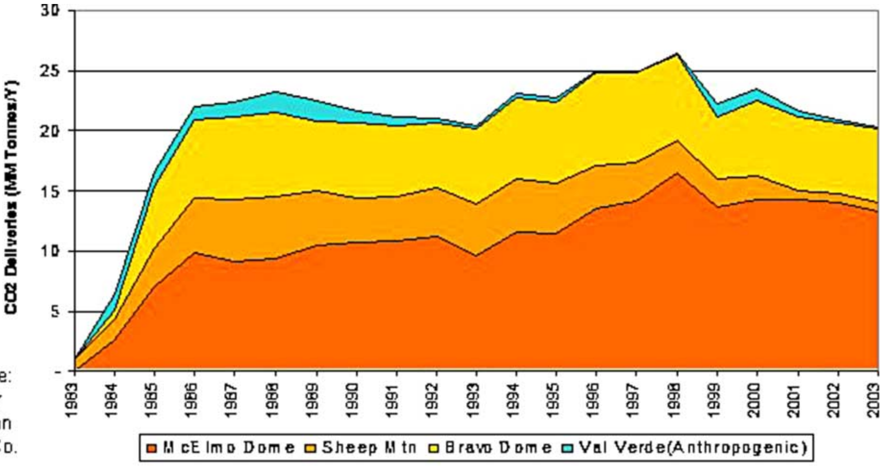
Implications for Geologic Storage

St. Johns Dome

St. Johns Dome is a large but operationally immature CO_2 field. It is not yet as well defined as the Jackson or McElmo Dome CO_2 fields. In addition, the thin anhydrite cap rocks, the large bounding fault that reaches to surface, and the presence of CO_2 in groundwater across this fault (but less so apparently directly above the field itself) all suggest that cap rock integrity may be somewhat less secure than at the two other sites (or, alternatively, that too much CO_2 was generated causing overspill of the structure into the adjoining fault block). On the other hand, St. Johns is the only field studied that traps significant He, a highly fugitive molecule. The field is a good analog for storage sites with cap rock uncertainty, as well as shallow settings where gas is stored in the free state.

Jackson Dome

Jackson (Pisgah) Dome is significant in that it securely contains CO_2 at extreme pressure, 50% above the hydrostatic gradient. Yet, its cap rock is neither salt nor shale, but rather carbonate. Jackson Dome is a good



Source: Kinder Morgan CO_2 Co. LLC

Figure 4: Production from McElmo Dome and other CO_2 fields.

analog for Gulf of Mexico area storage sites. The challenging and somewhat dangerous operating conditions (deep, overpressured, toxic H_2S) make its accident-free operation an excellent example of industry's capability to handle relatively tame storage projects (which are likely to be developed in low-pressure, well-characterized reservoirs).

McElmo Dome

McElmo Dome is the largest and operationally most mature commercial CO_2 field and possibly the best analog for future geologic storage sites, particularly in the Colorado Plateau. CO_2 has been stored at this field for approximately 70 million years, implying that geologic storage can be sufficiently long term in favorable settings. The porous, permeable dolomitized carbonate reservoir is continuous and CO_2 floats atop a regional aquifer; in this regard it is an excellent model for storage reservoirs. The thick salt cap rock at McElmo Dome appears to resist and accommodate faulting. The field's 20-year safe and environmentally sound operating record provides a good foundation for permitting storage sites. The field's tubular, cement, and monitoring technologies are appropriate for the several-decade field life, but upgrades would be needed for long-term ($>$ 10,000 year) CO_2 storage.

CONCLUSIONS

1. CO_2 accumulation is a natural process in many geologic settings. Prior to being developed, the three study sites stored 2.4 billion t (46 Tcf) of CO_2, equivalent to over 1 year of power plant emissions in the USA. They are comparable in size to the largest proposed individual storage sites. This evidence provides justification for industrial-scale geologic storage as an environmentally compatible GHG mitigation option.
2. Reliable reservoir seals require evaporites, shales, or low-permeability carbonates as the cap rock. Complementing parallel modeling and laboratory studies, study of natural analogs demonstrates empirically that, in favorable settings, CO_2 has been stored essentially "forever" (on human timescales; possibly 70 million years at McElmo and Jackson Domes) with no major adverse impacts on reservoir and cap rock. Thick salt cap rocks (such as the 400 m of halite at McElmo Dome) appear nearly impermeable and self-sealing to faults over geologic time in tectonically stable locations. Anhydrite (St. Johns Dome) and carbonate (Jackson Dome) also can be highly effective cap rocks. Remarkably, Jackson Dome's cap rock has contained excess pressures 50% above hydrostatic levels, probably for millions of years. We recognize that every geologic setting is unique and it is not

realistic to formulate universal criteria for cap rock integrity based on our limited study. Nevertheless, this information can provide guidelines useful for screening candidate CO_2 storage sites, particularly in similar geologic settings. To build confidence, early storage site selection would benefit from CO_2 field analog characteristics, such as the presence of thick and secure evaporite, shale, or carbonate cap rocks.

3. Natural CO_2 production practices provide valuable "lessons learned" for CO_2 storage. During the past two decades, the commercial CO_2 production industry has developed safe and cost-effective CO_2 production, processing, monitoring, and safety techniques and equipment that can be adapted for long-term storage of CO_2. The study fields are collectively producing 18.5 million t/year (986 MMcfd) of CO_2 for commercial use, mainly EOR. Corrosion control is achievable with chromium steel, carbon steel with amine carbon gauze coatings, batch corrosion inhibitors (e.g. $NaHCO_3$), or cathodic protection of flowlines; corrosion surveillance using boroscope, ultrasound, weight-loss coupons, and other methods. Wireline-set plugs downhole can automatically shut in the well in case of accidental damage to the wellhead. However, certain components (e.g. well casing, cements, etc.) would need to be upgraded to withstand the much longer time scale required for geologic storage projects. For example, CO_2-resistant cements may be adequate for short-term applications (decades), but require advancements to withstand the longer lifespans of geologic storage.
4. Efficient operation of CO_2 storage will require its own set of practices and technologies. Despite the encouraging evidence and lessons learned of long-term secure CO_2 storage at the three study fields, future geologic storage sites will differ in several important respects. For example, a depleted oil and gas field will have significant remaining hydrocarbons, whereas the studied natural analogs are essentially pure CO_2 with minimal contaminants. Also, the natural accumulation took many thousands of years to fill, yet storage sites may inject CO_2 for a few decades or less.

RECOMMENDATIONS

The three natural CO_2 fields assessed in this study have yielded considerable information relevant to long-term anthropogenic CO_2 storage, including storage capacity, storage period, cap rock type and other factors (Table 2). However, there are areas where natural analogs fail to provide needed data for evaluating geologic storage, such as the impact of rapid fill rates or long-term well cementing technology. Furthermore, the three natural analogs alone cannot prove the case for safe, long-term storage in every geologic province. Additional work identified by this study that could help advance CCP's goals in this area include:

- Develop a worldwide database of natural CO_2 deposits to help identify geologic provinces that are particularly suitable for long-term storage, as they already have demonstrated natural CO_2 trapping. The database also would provide a set of storage analogs that could be used to evaluate the potential effectiveness of projects in similar formations and structures.
- Profile other natural analogs in high-priority storage basins located near major anthropogenic CO_2 sources (such as Appalachia, Alaska, the Middle East, Russia, China, Southeast Asia, etc.). Even if they are smaller deposits or have lower CO_2 concentrations, they are more likely to closely resemble local storage projects and thus could help strengthen scientific and public confidence.
- The CO_2 fill rate of natural analogs was probably very slow (thousands, perhaps millions of years) compared to the decades likely for engineered storage sites. A well-characterized depleted natural CO_2 field (e.g. McElmo Dome) should be simulated to model the efficiency and safety of rapid re-fill rates, including hysteresis effects and tensional stress changes on the cap rock.
- Natural CO_2 field cap rocks are not normally cored, thus there is little direct data on their composition, texture, fracturing, and chemistry that make them such excellent seals. The cap rock of a well-characterized depleted CO_2 field should be cored for detailed analysis.
- Soil gas analysis has not been performed at the study sites, yet this information could help confirm or disprove cap rock integrity.
- Develop new CO_2-resistant cements designed to withstand exposure for $> 10{,}000$ years, rather than the current time scale of decades.

TABLE 2
SUMMARY OF KEY SIMILARITIES AND DIFFERENCES BETWEEN NATURAL CO_2 FIELD ANALOGS AND FUTURE GEOLOGIC SEQUESTRATION SITES

Factor	Natural analog	Sequestration site	Assessment	Work needs
Storage capacity	0.1–2.4 Gt	Comparable	Good analog	None
Storage period	Millions of years?	> 10,000 years	Good analog	Noble gas analysis
Cap rock	Salt best; shale or anhydrite good	Comparable	Good analog	Coring and characterization of cap rock at natural analog sites
Fill rate	Slow	Fast	Poor analog	Model re-filling a depleted CO_2 field
Operation objective	Withdrawal	Injection	Poor/Fair	Conduct test injection at analog
Cement life	Decades	> 10,000 years	Poor	CO_2-resistant cements

NOMENCLATURE

‰	parts per thousand
CCP	CO_2 Capture Project
cm	centimeter
D	Darcy
Fm	Formation
GHG	greenhouse gas
GIS	geographic information system
kg	kilogram
km	kilometer
lbs	pounds
m	meter
mD	millidarcy
Ma	million years ago
mW/km^2	milliwatt per square kilometer
MMcfd	million cubic feet per day
MMscf	million standard cubic feet
MPa	megapascal
ppm	parts per million
psi	pounds per square inch
SVF	Springerville Volcanic Field
t	metric ton
Tcf	trillion cubic feet

ACKNOWLEDGEMENTS

The author thanks the Carbon Capture Project and U.S. Department of Energy for funding this study and Denbury Resources Inc., Kinder Morgan CO_2 Co. LLC, and Ridgeway Petroleum Corp. for contributing data. The author also recognizes the contributions of Chris Ballentine, Keith Bowman, Chuck Fox, Stuart Gilfillan, Stephen Melzer, Curt Oldenburg, Martin Schoell, Scott Tye, and anonymous reviewers.

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