



# Article Multiscale Assessment of Caprock Integrity for Geologic Carbon Storage in the Pennsylvanian Farnsworth Unit, Texas, USA

Natasha Trujillo <sup>1,†</sup>, Dylan Rose-Coss <sup>1,‡</sup>, Jason E. Heath <sup>2</sup>, Thomas A. Dewers <sup>3,\*</sup>, William Ampomah <sup>4</sup>, Peter S. Mozley <sup>5</sup> and Martha Cather <sup>4</sup>

- <sup>1</sup> New Mexico Institute of Mining and Technology, Earth and Environmental Science Department, Socorro, NM 87801, USA; natasha.trujillo@pxd.com (N.T.); dylanh@state.nm.us (D.R.-C.)
- <sup>2</sup> Sandia National Laboratories, Geomechanics Department, Albuquerque, NM 87185, USA; jeheath@sandia.gov
- <sup>3</sup> Sandia National Laboratories, Nuclear Waste Disposal Research and Analysis, Albuquerque, NM 87185, USA
  <sup>4</sup> New Mexico Institute of Mining and Technology, Petroleum Resource Recovery Center,
- Socorro, NM 87801, USA; William.Ampomah@nmt.edu (W.A.); Martha.Cather@nmt.edu (M.C.)
- New Mexico Institute of Mining and Technology, Associate Vice President for Academic Affairs and Earth and Environmental Science Department, Socorro, NM 87801, USA; Peter.Mozley@nmt.edu
- \* Correspondence: tdewers@sandia.gov; Tel.: +1-505-845-0631
- + Present address: Pioneer Natural Resources Company, Midland, TX 75039, USA.
- Present address: New Mexico Oil Conservation Division, Santa Fe, NM 87505, USA.

Abstract: Leakage pathways through caprock lithologies for underground storage of CO<sub>2</sub> and/or enhanced oil recovery (EOR) include intrusion into nano-pore mudstones, flow within fractures and faults, and larger-scale sedimentary heterogeneity (e.g., stacked channel deposits). To assess multiscale sealing integrity of the caprock system that overlies the Morrow B sandstone reservoir, Farnsworth Unit (FWU), Texas, USA, we combine pore-to-core observations, laboratory testing, well logging results, and noble gas analysis. A cluster analysis combining gamma ray, compressional slowness, and other logs was combined with caliper responses and triaxial rock mechanics testing to define eleven lithologic classes across the upper Morrow shale and Thirteen Finger limestone caprock units, with estimations of dynamic elastic moduli and fracture breakdown pressures (minimum horizontal stress gradients) for each class. Mercury porosimetry determinations of CO<sub>2</sub> column heights in sealing formations yield values exceeding reservoir height. Noble gas profiles provide a "geologic time-integrated" assessment of fluid flow across the reservoir-caprock system, with Morrow B reservoir measurements consistent with decades-long EOR water-flooding, and upper Morrow shale and lower Thirteen Finger limestone values being consistent with long-term geohydrologic isolation. Together, these data suggest an excellent sealing capacity for the FWU and provide limits for injection pressure increases accompanying carbon storage activities.

Keywords: carbon sequestration; caprock integrity; noble gas migration; seal by-pass

# 1. Introduction

The Site Characterization program of the Southwest Regional Partnership on Carbon Sequestration (SWP) assesses the integrity of caprock formations that immediately overlie the Pennsylvanian Morrow B sandstone, which is the target reservoir for a combined carbon capture, utilization, and storage (CCUS) project involving enhanced subsurface oil recovery (EOR)–CO<sub>2</sub> storage at the Farnsworth Unit (FWU), Texas, USA. Caprock integrity is the ability of generally low permeability and high capillary entry pressure formations overlying a reservoir—typically referred to as caprocks—to impede movement of fluids from the reservoir below and thus display sealing. Capillary sealing behavior arises from the nanoscale pore throats and interfacial fluid properties of the wetting



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). phase in the caprock (e.g., brine) and the non-wetting phase of the reservoir (e.g.,  $CO_2$  or hydrocarbons). However, caprocks may contain "seal-bypass systems", which are features and/or processes that allow reservoir fluids to move out of the reservoir [1], while wettability of reservoir and caprock can be altered by carbon storage and/or enhanced hydrocarbon recovery procedures [2]. Seal-bypass systems may include discontinuous coverage of the sealing lithologies over the reservoir, natural or induced fracture networks, faults, permeable injectites (i.e., structures formed by sediment injection) or other geologic pipe structures, and man-made intrusions such as leaky wellbores [1]. Implicit in the concept of caprock sealing behavior is a timescale of interest, which for geologic  $CO_2$  storage is 100 s to 1000 s of years.

This chapter presents a novel caprock integrity study that focuses on evaluating geologic sealing behavior for capillary, fluid flow, and mechanical properties at different spatial and temporal scales. Specifically we assess: 1. Pore-scale capillary sealing and microstructure; 2. local seal bypass mechanisms; 3. seal regional lateral continuity across reservoir scales; 4. mechanical integrity of the reservoir-caprock package to fluid pressure perturbation; and 5. reservoir-scale hydrologic isolation over relevant time scales. This requires a multiscale approach using a variety of techniques to cover the range of length and time scales, processes, and features involved in caprock integrity (Figure 1). To these ends we examine well log- to sub-core scale heterogeneity of the reservoir and sealing lithologies of the Morrow B sandstone lithologies, the upper Morrow shale top seal, and the overlying Thirteen Finger limestone secondary sealing lithologies. Capillary heterogeneity is examined using mercury porosimetry. We examine evidence for existing fractures and faults that could serve as seal bypass systems under present day stress orientations, as well as geomechanical constraints on induced seal bypass features associated with CCUS and EOR activities within the FWU. The lateral continuity of sealing units in the FWU is assessed via subsurface mapping. The large-scale sealing capacity of these lithologies as have occurred over the geologic time is assessed using noble gas measurements collected from fresh core. Formation-scale features examining the scale of the entire FWU and regional stratigraphic architecture using seismic methods have been discussed by Rose-Coss et al. [3,4] and Ampomah et al. [5]. Together this data set provides a unique timeintegrated assessment of caprock integrity over engineering to geologic time- and lengthscales relevant to CCUS.





10-2

**Figure 1.** Features, processes, and measurement resolution relevant to the assessment of caprock integrity (adapted from the original Figure 36 in [6] and the modification thereof in Figure 1.1 in [7]).

## 2. Site Location and Geologic Setting

10<sup>-10</sup>

10-8

10<sup>-6</sup>

10<sup>-4</sup>

2.1. Unit History and General Geology

The FWU is located in Ochiltree county, Texas, USA (Figure 2), with the nearby Arkalon Ethanol Plant and Agrium Fertilizer Plant supplying anthropogenic  $CO_2$  for enhanced oil recovery in the field. Production and injection at FWU occur strictly within the Pennsylvanian Morrow B sandstone (Figure 3; [5]). "Morrow" is an operational name that refers to a sequence of alternating mudstone and sandstone intervals deposited during the Morrowan period of the late Pennsylvanian [8]. The Morrow B delineates the first sandstone package deposited below the Atokan Thirteen Finger limestone [9,10].

The primary caprock intervals at FWU are comprised of the upper Morrow shale and the Thirteen Finger limestone (both operational names/units in the FWU; Figure 3). The Thirteen Finger limestone is an informal name for a series of predominantly carbonate

cementstone intervals that are intercalated with black carbonaceous mudstone deposited during the Atokan period of the late Pennsylvanian (Figure 3; see also Trujillo [10] and Rose-Coss [9]).



**Figure 2.** Locations of wells in the Farnsworth Unit (outlined in blue) used in assessing local and field-wide caprock integrity. Red lines in show locations of inferred faults (modified from Balch and McPherson [11] and Hutton [12]).

Both the Morrowan and Atokan intervals are common throughout the Texas and Oklahoma panhandles, southeastern Colorado, and western Kansas. Overlying stratigraphy includes Late Pennsylvanian through the Middle Permian shales and limestones, with lesser amounts of dolomite, sandstone, and evaporites [8,12–14].

## 2.2. Tectonic Setting

The FWU sits on the northwest shelf of the Anadarko basin in the Texas Panhandle. From the FWU, the basin plunges to the southeast where it reaches depths of over 40,000 ft (12,192 m) adjacent to the Amarillo-Wichita Uplift [15,16]. Maximum rates of subsidence occurred during Morrowan to Atokan times [14–17]. Positive features which might have influenced deposition within the region include the Ancestral Rockies to the north, the Central Kansas uplift to the north-east, and the Wichita-Amarillo uplift to the south [17,18]. The structural grain of the basin was inherited from the Precambrian to Cambrian failed arm of a triple junction known as the Southern Oklahoma Aulacogen [15,16]. The region was then tectonically quiet until the beginning of the Chesterian-Morrowan, when the Wichita-Amarillo uplift and the ancestral Rockies formed as a result of the northeast-directed basement-involved thrust faulting associated with collision between the North American and Gondwanan plates [14,15,19,20]. Fault movement within the Wichita-Amarillo uplift is characterized by the vertical block movement and left-lateral strike slip movement. The vertical fault movement began in the Chesterian and then continued predominantly at the end of the Morrowan into the Atokan time period [17]. This period of faulting created normal faults with a down-to-the-south displacement parallel to the axis of shear associated with the Amarillo uplift. The left-lateral strike slip movement occurred afterwards in the late-to-post Atokan and is expressed as anticlinal horst blocks and synformal grabens diverging at intersections from the main shear zones [17]. Tectonic activity slowed after the Atokan and the region was quiescent by the end of the Pennsylvanian. Local uplifts and associated basins combined with climate variations at time of deposition set the stage for the stratigraphic variations seen in the core, and especially evident in the Thirteen Finger limestone.



Figure 3. Stratigraphic columns of three SWP characterization wells (modified from Rose-Coss [9]).

## 3. Materials and Methods

## 3.1. Coring Program, Petrologic Description, and Well Log Analysis

The coring program was designed and implemented in 2013 and 2014 by the SWP and former operator Chaparral Energy LLC, which targeted the primary Morrow B sandstone reservoir and the overlying caprocks, the upper Morrow shale, and the Thirteen Finger limestone. The coring program included core analysis plans to support major SWP project objectives and/or research topics on CO<sub>2</sub> storage capacity, injectivity, and plume extent; storage permanence; and injection- and/or production-induced reservoir damage, and included a suite of petrophysical, petrological, geomechanical, and geochemical testing.

Schlumberger ran a large suite of wire-line tools for caprock and reservoir characterization, and wellbore integrity assessment in cooperation with the SWP, which had personnel in the field to observe drilling and coring of Well 13-10 A and 13-14, and to assist with core preservation and core handling. Terra Tek, now a Schlumberger company, performed core handling in the field and initially housed the core for initial characterization and sampling. Initial core reviews were performed by Sandia National Laboratories (SNL), New Mexico Tech (NMT), and Chaparral Energy to choose sample locations for petrologic, petrophysical, geomechanical, and geochemical analysis to be performed by Terra Tek, SNL, and NMT. SNL and NMT coauthors submitted formal plans to Terra Tek, which included sampling and/or analysis for thin sections (of the caprocks and reservoir rocks and of fractures), relative permeability and capillary pressure, routine plug analysis, mercury porosimetry, Routine Core Plug (RCPA), and Tight Rock Analysis (TRA) (both by Terra Tek), X-ray diffraction, geochemical analyses including pyrolysis and vitrinite reflectance, and geomechanical testing.

To help quantify heterogeneity and guide sampling densities for laboratory testing, the multi-well Heterogeneous Rock Analysis (HRA; [21]) was performed by Schlumberger using proprietary methods. For HRA of FWU reservoir and caprock lithologies, results of gamma ray, deep resistivity, bulk density, neutron porosity, and compressional slowness logs were combined with caliper responses to make a preliminary assessment of rock classes, which resulted in determining eleven separate rock unit classes: Two for the reservoir lithology (Morrow B) and nine for the caprock lithologies (upper and lower Morrow shale and Thirteen Finger limestone). More discussion on core descriptions and core photographs are found in Rose-Coss [9] and Trujillo [10].

## 3.2. Petrologic Characterization

Petrologic methods involved standard optical thin-section petrography and backscattered electron microscopy conducted at both SNL and NMT, using methods described by Rose-Coss [9] and Trujillo [10] and facilities at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and New Mexico Tech. We report here on some backscattered imaging results, with additional details and petrography given by Rose-Coss [9] and Trujillo [10].

## 3.3. Petrophysics

Detailed descriptions of methods used in the report analysis of the coal and organicrich shales (performed by Terra Tek) are given by Rose-Coss [9]. Descriptions of Terra Tek tight rock analysis and pressure pulse decay methods for permeability of caprock lithology core plugs are given in Trujillo [10]. Intrusion-extrusion mercury porosimetry was performed on core plugs by Poro-Technology, a Micromeritics company, using a Micromeritics AutoPore IV 9500 Series porosimeter. Core plugs were oriented either vertically or horizontally (i.e., parallel or perpendicular to the long axis of the core). The core plugs were approximately 0.9-inch (2.3 cm) diameter by 0.9-inch (2.3 cm) long and were jacketed with epoxy for directional intrusion. Poro-Technology made closure corrections accounting for volumes of mercury injected that did not penetrate into the pore space prior to the pressure achieving the mercury entry pressure of the pore space. Breakthrough pressure or the pressure at which a non-wetting phase penetrates a rock through the connected pore space [22], was estimated for core plugs using methods of Dewhurst et al. [23]. Breakthrough pressures were converted from the mercury-air system to a CO<sub>2</sub>-water system and to CO<sub>2</sub> column heights using the methods of Ingram et al. [24]. We use an interfacial tension value of 484 mN/m for the mercury-air-rock system, and a contact angle of 140°. We assumed a geothermal gradient of 25 °C/km and a hydrostatic pressure gradient of 0.0098 MPa/m to estimate the density of CO<sub>2</sub> and water at the depths of the core plugs. Interfacial tension values for the water-CO<sub>2</sub> system assumed zero ionic strength and used the methods of Heath et al. [25]. Contact angles for the water-CO<sub>2</sub>-mineral system were estimated from Iglauer et al. [26] for quartz, calcite, and mica, resulting in a range of 10 to 57°.

#### 3.4. Geomechanics

A series of rock mechanical tests were performed on rock core sampled and tested at Terra Tek's laboratories in Salt Lake City, Utah, using standard techniques. These include Brazil tension (or cylinder splitting) tests, unconfined compression tests, and triaxial compression tests. These were used to extract static elastic properties, rock unconfined and triaxial strength, and tensile strength information from samples from all three SWP characterization wells in the FWU. A standard Mohr-circle analysis was used to delineate failure envelopes for sampled lithologies.

#### 3.5. Fracture Analysis

Under the guidance of coauthors, Terra Tek performed a detailed analysis of macroscopic fractures on nearly 270 ft of continuous whole core from Well 13-10A. The fracture descriptions focused on identifying fracture types based on morphologic characteristics and intensity. As the core was not oriented, Terra Tek drew an arbitrary "North" line on the core to enable the measurement of relative orientation of measured fractures. Fracture attributes measured include fracture strike and dip relative to this North line, general fracture type, type of mineral fill, type of oil stain, fracture porosity, fracture spacing, and intensity of fractures for each cored interval. Fracture classes include those induced from drilling or coring versus natural fractures that may or may not exhibit shear, extension or mineralization. Terra Tek analysis included tabulation of fracture types by depth and stereo plots of relative fracture orientations by fracture type.

## 3.6. Preservation of Fresh Core and Noble Gas Analysis

Core preservation for noble and other pore fluid gases followed procedures found in Osenbrück et al. [27]. Especially, designed canisters were built from high-vacuum service equipment to seal samples against atmospheric contamination. Sub-samples of core were weighted and sealed in canisters immediately in the field after the core was retrieved to the Earth. A purging and vacuum pump-down process evacuated atmospheric noble gases from the canisters using methods described by Heath [7]. Helium, neon, and argon isotopes were analyzed at the University of Utah Dissolved and Noble Gas Laboratory in Salt Lake City, Utah, USA. After the transfer of gases into a purification line, the analysis followed the methods described by Hendry et al. [28].

#### 4. Results

As stated in the introduction, assessing caprock integrity for EOR-CCUS involves a multiscale examination of the ability of a caprock lithology or set of lithologies to sustain emplacement of a body of  $CO_2$  for a given time. For CCUS, this may be 100 s or 1000 s of years. One aspect for CCUS that is favorable for use of  $CO_2$  for oil recovery and storage is the fact that the same caprock invoked for  $CO_2$  uses the same caprock involved in oil and gas storage over the geologic time. We know from the long history of subsurface engineering at FWU that storage under EOR conditions is favorable for  $CO_2$  containment. We need to build confidence that injection and emplacement conditions under CCUS best practices does nothing to threaten the integrity of sealing potential of caprock lithologies.

To this end, we examine the integrity of the FWU upper Morrow shale and Thirteen Finger limestone from five perspectives: 1. Characterizing the heterogeneity within the caprock lithologies from well logging and core properties; 2. characterizing the capillary heterogeneity of unfractured lithologies and calculating abilities to sustain a capillary seal to  $CO_2$  of a given volume or column height; 3. evaluating the potential of existing fractures and faults to serve as seal bypass features, as well as assessing the potential for creation of new fractures or reactivating old ones under injection-perturbed stress conditions; 4. characterizing the physical, stratigraphic continuity, and consistency/heterogeneity in the caprock lithologies over the reservoir extent; and 5. assessing the sealing capacity over the geologic time using noble gas distributions. Together, these five topics constitute a multi-length and -time scale assessment of caprock integrity for CCUS at the FWU.

# 4.1. Heterogeneity at "Well Log"- to Core-Scales

Well logging has been the stalwart of petroleum exploration in determining rock heterogeneity and its application for CCUS, which is of special import for the sealing potential in that core recovery of delicate mudstone lithofacies, is difficult. A workflow for the caprock analysis begins with well logging, proceeds to core description and analysis (if the core is available), and then to subsampling for laboratory analysis. In this section, we utilize the Terra Tek HRA to categorize the FWU reservoir and caprock into eleven distinct lithofacies, which are mapped onto core descriptions and form a basis for subsequent core plug sampling and analysis including mercury porosimetry and mechanical testing.

## 4.1.1. Lithofacies Interpretations of Caprock Units

Figure 3 shows stratigraphic columns of each core obtained from the three characterization wells at Farnsworth (the 13-10A, 13-14, and 32-8), depicting the extent of mud and sand in the clastic mixture, including fractured zones, depositional fabrics (i.e., carbonate hardgrounds, burrows, and coal cleats), and diagenetic features (i.e., carbonate "beef", concretions, and mineralized fractures) that could exert positive or negative influences on caprock integrity. Details about these features are found with the accompanying core descriptions in [9,10].

The upper Morrow shale is a marine mudstone that directly overlies the Morrow B sandstone reservoir (Figure 3) and thus serves as the primary caprock. It is composed of three common mudstone lithofacies (Table 1) including the black laminated mudstone (blM), calcareous mudstone.

The (cM) and green bioturbated mudstone (gbM) as determined by [9]. The lower portions of the upper Morrow shale consist of the gbM facies, which is transitional from the sands of the Morrow B reservoir. The green bioturbated mudstone (gbM) lithology is a slightly fossiliferous, organic-rich, slightly calcareous mudstone, that contains scattered quartz, feldspar, muscovite, and calcareous fossil-hash silt. The middle portion of the upper Morrow shale consists of the blM facies, which is interpreted by [9] to be deposited under anoxic conditions, consisting of fissile, slightly fossiliferous organic-rich mudstone. This facies gradually transitions upward into the cM facies, a more friable and calcareous mudstone that contains several hardgrounds (i.e., cemented paleo sea-floor surfaces) that are found to be laterally continuous through the FWU [9,10]. The variable degree of cementation in the cM facies imparts a heterogeneity to the geomechanical response, as discussed later.

The overlying Thirteen Finger limestone was deposited in a marine environment that underwent several cycles of transgression and regression during deposition [29] and consists mostly of black carbonaceous mudstone (bcM) lithofacies alternating with limestone layers [9,10]. On inspection, the limestone layers consist of diagenetic carbonate cement or diagenetically enhanced carbonate content and thus are denoted as cementstone lithofacies (cC; [9,10]). Fossil hash concentrations and pyrite nodules occur in varying amounts throughout the mudstone lithology, and there are some coal seams of varying thickness. The Thirteen Finger limestone is a widely distributed formation with a distinct

wireline log signature with recognized open and healed vertical fractures that may provide a permeable network, especially towards the top of the unit [29,30].

**Table 1.** FWU caprock lithofacies descriptions (after Rose-Coss, 2017 [9]), TOC analysis, and assigned color for HRA rock classification (Terra Tek).

Facies and Description	Sedimentary Features	TOC%	HRA Color							
Thirteen Finger limestone										
(cC) Carbonate cementstone, micritic dolomite, and dedolomite, grey to white	Well indurated, smooth, sparse cemented fractures, abrupt to gradational bounding surfaces	2.3	Light Blue							
(bcM-a) Well indurated black carbonaceous mudstone and siltstone, locally calcareous	pyrite nodules, fossil hash, bioturbation, bedding-parallel fibrous calcite veins ("beef" of Cobold, 2013)	0.44–10.7	Black							
(bcM-b) Fairly well indurated carbonaceous black mudstone	Floating sand grains, abundant to moderate burrowing	0.44–10.7	Purple							
(bcM-c) Black mudstone and coal	Coal with thin layers of mudstone	0.44–10.7	Olive							
(bcM-d) Black to grey laminated mudstone with silt partings	Locally dolomitic, fossiliferous, organic rich partings (plant fragments)	0.44–10.7	Orange							
(bcM-e) Poorly indurated black carbonaceous mudstone	Locally dolomitic, fossiliferous	0.44–10.7	Grey							
Morrow shale										
(cM) Calcareous mudstone, brown to grey, green laminated to massive, broken and bioturbated sections, friable	Slightly fossiliferous, laminations, bioturbation, coal	0.44–10.7	Brown							
(blM) Black, laminated mudstone	Low angle to planar laminations, concretions, fossil hash	0.53–2.7	Red							
(gbM) Friable, bioturbated mudstone, olive to gray, laminated to massive, friable	Low angle to planar weak laminations, low to moderate bioturbation, abundant microfossils	0.30–1.0	Yellow							

The caprock lithofacies in Table 1 are mapped onto the Terra Tek HRA classification scheme as described in [31] denoted by the colors in the last column of Table 1. Note that the Terra Tek HRA procedure recognizes the variability in the mechanical integrity of the bcM lithofacies of the Thirteen Finger limestone, and we have denoted this by additional labels (i.e., bcM-a, bcM-b, etc.). Figure 4 summarizes the results of the HRA performed by Terra Tek from the well log variability in Well 13-10A [31]. The HRA facies designations are shown by the color strip down to the middle of the figure, and one can discern the Morrow B sandstone (dark blue), lower Morrow shale (red), upper Morrow shale (yellow, red, and brown going from deep to shallow), and the Thirteen Finger limestone, with multiple alternating bands of color. The lithologic breaks in the Thirteen Finger limestone are easily discernable from gamma and density logs, for example, a close examination of the density logs and gamma ray "kicks" reveals the storied thirteen shale members of the Thirteen Finger limestone alternating with the carbonate layers (designated by the light blue color bands). Variability in the mechanical integrity within the shale layers of the Thirteen Finger limestone is manifested in five distinguishable subunits of the bcM lithology, shown by separate colors. Later, we distinguish these layers in terms of mechanical behavior, and, for example, moving from elastically stiff to compliant layers we would have the HRA color designations Black > Purple > Olive > Orange > Grey. HRA logs for Wells 13-14 and 32-8 are given by Figures S1 and S2 in the Supplementary Materials accompanying this paper. The HRA analysis is commonly performed in the realm of unconventional "shale" reservoirs [21,32,33] and is a means to better understand the mudstone lithological variability given the poor core recovery and general difficulty in obtaining core-plug

samples for standard analyses, which can lead to a sampling bias and over-representation of the strengths of these materials.

A mapping of HRA color designations and facies designations from core logging performed by Rose-Coss [9] is facilitated by petrographic observations from thin sections prepared from the core obtained from the 13-10A, 13-14, and 32-8 Wells. These were performed by Steve Cather of the NMBGMR (Personal Communication, 2017) and are summarized in Tables S1–S3 in the Supplementary Materials. From this, we determine that the Orange HRA refers to Bcm facies with more abundant carbonate, the Olive designation refers to coal layers and the black mudstone above and below that encapsulates them, and the grey Bcm lithofacies is the least indurated, and as such has the least values of dynamic and static elastic moduli (shown later). Black and purple HRA units are the most indurated of the bcM facies.

The caprock lithologies would classify as silt- (quartz, carbonate, organic matter) bearing clay-rich mudstone and clay-dominated mudstone (Figure 5A,B; classification of Macquaker and Adams [34]). From thin section observation [9,10], the mudstones contain variable amounts of organic matter, quartz, and macro and microfossils. Authigenic pyrite, calcite, and dolomite are common. Many of the cementstone layers contain fractures, which are commonly filled with carbonate cement [10]. The limestone is somewhat unusual, in that it is dominated by diagenetic carbonate (Figure 5C,D). The limestone locally contains a significant biogenic carbonate [10]. Thus, most of the limestones in the Thirteen Finger limestone are more properly classified as cementstones. This interpretation is supported by the obvious occurrence of concretions in the core (Figure 5D), which are similar in character to the limestone beds.

Although most of our attention is devoted to the caprock, we refer to lithologies in the Morrow B sandstone reservoir for comparison purposes. Lithologic descriptors associated with the color codes for the Morrow B sandstones are far simpler and relate to the hydrologic flow units discussed by [2,4], carrying a dark blue or green HRA designation as shown in Figure 4 above and Figures S1 and S2 in the Supplementary Materials.

# 4.1.2. Porosity and Permeability of Sealing Lithofacies

With the HRA mapped onto core descriptions, representative core plugs of the eleven lithofacies were analyzed for porosity, water and oil saturation, and gas permeability via Terra Tek's RCA at depth intervals of approximately 3 ft if core plugs were attainable, and these are mostly Morrow B (reservoir) lithologies. Data for Well 13-10A are given in the Appendix of Rasmussen et al. [2], data for the other two Wells (13-14 and 32-8) are given in Table S4 in the Supplementary Materials, color coded by the HRA rock class. Here, we present the porosity and permeability of the mudstone and limestone lithofacies that were recoverable in the coring and represent the sealing lithologies for CO<sub>2</sub> containment at FWU. The relatively poor core recovery of mudstones is evident as a sampling bias with more core plug data evident from the Morrow B sandstone and the Thirteen Finger limestone lithologies.

These results are summarized in Table S5 for all three characterization wells and are mapped to both the caprock facies designation of [9] and the HRA color unit. In Figure 6, we plot the total porosity and permeability by depth for mudstone and limestone members of the Morrow B sandstone (depth range shown in purple), the overlying upper Morrow shale (depth range shown in green), and of the Thirteen Finger limestone (depth range shown in pink). Although there is well-to-well variability, in general, the Morrow shale mudstones have higher porosity and slightly higher permeabilities of the hydrologic flow units in the Morrow B sandstone are considerably higher, with porosity values ranging largely from 15 to 20%, and permeability ranging from 10 to 1000 mD (orders of magnitude higher than the mudstone facies of the caprock units at FWU shown in Figure 6; see Figure 2 in [2]).

Log Depth	Core Depth		Tops	Gamma Ray & Caliper Logs	Resistivity Logs	Porosity & Lithology Indicator Logs	ECS Mineralogy Logs	HRA Rock Classes	HRA Error	Core Total Gamma Ray	Core Uranium	Core Thorium	Core Potassium
MD (ft) 1:240	CDEPTH (ft) 1:240 - 7470	WC_INTERVAL BILFLAC	TOPS_CHAPARRAL	BS/HDAR HSGR 0 GAP1 300 GRT0 0 HDAR 6 IN 15 BS 6 In 15	AT90 0.2 ohm.m 2000 AT50 0.2 ohm.m 2000 AT30 0.2 ohm.m 2000 AT20 0.2 ohm.m 2000 AT20 0.2 ohm.m 2000 AT10 0.2 ohm.m 2000	Density Correction        RHOZ        1.95      G/C3      2.95        TMPH      0.45      CFCF      -0.15        PEFZ      0      B/E      10        DTCO      DTCO      240      us/ft      40        DTSM_FAST      40      HDRA      -0.2      G/C3      0.6	PYRITE ANHYDRITE CARBONATE Q-F-M CLAY	HRA_TAG2MORROW	ERR>40 ERR_HRA 0 100	GRTO 0 API 800	GRUR 0 PPM 40	GRTH 0 PPN 40	GRK 0 % 4
- 7480 - - 7500 - - 7500 - - 7530 - - 7530 - - 7530 - - 7550 - - 7	7480 - 7490 - 7500 - 7550 - 75		Thirteen Finger		- Mannan -	MUMMenter Contraction	MAAAAAAAAA		when the when he had he had a for the second of the second s	Mr Mr Mr Mr Mr Mr	Ammun Mr. M. A.M.	My My My My My My	1 m M M M M M
7610 7620 7630 7640 7640 7650 7660 7660 7670	7610 - 7620 - 7630 - 7660 - 7660 - 7660 - 7680 - 7680 -		Iorrow B Morrow Shale	Morrow B					and the second		mon Am	Man Jun Mary	man man
7700 - 7710 - 7720 - 7730 - 7740 - 7750 - 7750 - 7760 -	7700 7710 7720		X				M				A CARACTER AND A CARACTER ANTER	MMM	MM

**Figure 4.** Well 13-10A heterogeneous rock analysis log showing the color by the rock unit and depth. Depths are given in feet and converted to meters by multiplying by 0.3022. Note that the logging depth and coring depth contain discrepancies associated with the coring procedures.



**Figure 5.** (**A**) Back-scattered electron image of a silt (carbonate, organic matter) bearing clay-rich mudstone in the Morrow shale. Stratigraphic-up is to the left, with siltier rich laminae on the left and clay-rich laminae on the right. Black portions are organic matter, and white features are pyrite framboids. Well 13-10A, 7633.76 ft. (**B**) Backscattered electron image of silt (quartz, calcite, organic matter) bearing clay-rich mudstone in the Morrow shale. Stratigraphic-up is to the left. Black particles are organic matter, irregular dark gray particles are quartz, light gray rhombs are ankerite, white grains are pyrite. Well 13-10A, 7632.6 ft. (**C**) Backscattered electron image showing calcite (light gray), dolomite (dark gray), and pyrite (white) cemented mudstone (cementstone) in the Thirteen Finger limestone, Well 13-10A, 7540.65 ft. (**D**) Core photographs showing the variable geometry of limestones in the Thirteen Finger limestone. Some limestones are laterally continuous throughout the width of the core, whereas other are laterally discontinuous (concretionary). Well 13-10A, depths indicated on the photo. See [9,10]) for additional images and descriptions.

## 4.2. Capillary Heterogeneity and Sealing Capacity

The sealing capacity in the context of CCUS is the  $CO_2$  column height that is retained by the capillarity of a water wet rock. Here, we estimate  $CO_2$  column heights (using calculated pore throat diameters and breakthrough pressures) for the different reservoirs and caprock lithologies using MICP analyses from core plug samples, which is summarized in Table S6 in the Supplementary Materials. The pore throat size distributions for the Morrow B sandstone, upper Morrow shale, and the Thirteen Finger limestone for the west and east side of the FWU are compared in Figure S3 and the accompanying text in the Supplementary Materials. There is a clear difference in the reservoir and sealing lithologies across the FWU as one would expect. The Morrow B sandstone pore throat diameters show a broad range over five orders of magnitude (0.0003 to 1000  $\mu$ m), whereas the upper Morrow shale and Thirteen Finger limestone show a much narrower range over two orders of magnitude (~0.003–0.1  $\mu$ m).



**Figure 6.** Porosity and permeability of Farnsworth mudstone lithofacies within the Morrow B sandstone (purple), Morrow shale (green), and Thirteen Finger limestone (pink) for Wells 13-10A, 13-14, and 32-8. Color schemes and depths correspond to those in Figure 3. Data were determined from the Terra Tek tight rock analysis (TRA) methodology.

The mercury porosimetry results were used to calculate the  $CO_2$  column heights for the caprock and reservoir formations using the standard methods [7] and are shown by depth for the three characterization wells in Figure 7. The  $CO_2$  column heights for the upper Morrow shale and the Thirteen Finger limestone range from 1000 to 10,000 m (3280–32,808 ft). The cementstone lithology in the Thirteen Finger limestone has 11,000 m of  $CO_2$  column height, with an average of 9000 m (29,527 ft). Two of the cementstone samples reached the upper limit of pressure 60,000 psi (414 MPa), that the MICP instrument is capable of sustaining, with no observable intrusion of mercury.

The mudstone lithologies within the upper Morrow shale and Thirteen Finger limestone have an average  $CO_2$  column height of 2900 m (9514 ft), with a range of 1000 to 10,000 m (3280–32,808 ft). Not unexpectedly, the caprock  $CO_2$  column height values are 1-to-2 orders of magnitude larger than the sandstone reservoir values and exceed the reservoir thickness, suggesting an excellent caprock integrity. The  $CO_2$  column heights for the Morrow B sandstone reservoir ranged from about 1 to 100 m (3.3–328 ft). These results would suggest that the Morrow shale and Thirteen Finger limestone caprock should provide an excellent capillary sealing for  $CO_2$  for CCUS operations in the FWU. Note that these results refer to the lithologic properties of the rock matrices themselves. In order to further examine the question of caprock integrity, we need to examine in detail the potential of various seal by-pass features both in the form of existing natural fractures and in the potential for inducing fractures during injection and operation phases of CCUS-EOR.





**Figure 7.** CO<sub>2</sub> column heights for Wells 13-10A, 13-14, and 32-8 determined from the MICP analysis. "MB" denotes the Morrow B sandstone; "UMS" denotes the upper Morrow shale, and "13 Finger" denotes the Thirteen Finger limestone.

## 4.3. Seal Bypass Potential and Mechanical Integrity

# 4.3.1. Natural and Induced Fractures

Natural fractures in mudstone lithologies can impact fluid-flow, fracture permeability, and mechanical strength of the rock [35], all critical aspects for caprock integrity. To understand how natural fractures impact the ability of FWU caprock lithologies to prevent CO<sub>2</sub> leakage, we need to characterize fracture apertures and density, as well as orientation spatially and in reference to the current in situ stress orientations. Orientation aspects are especially relevant as: 1. Fractures are generally strength-limiting at above-core length scales, and the increase in pore pressure can induce slip and permeability increases for suitably oriented fractures [36,37]; 2. fracture orientation with respect to the in situ local stress tensor affects aperture width and thus permeability; and 3. fractures induced by fluid injection, i.e., hydrofractures, propagate in directions dictated by the local stress tensor. It is also important to distinguish fractures induced by coring, as these are not indicative of the state of fracturing in the subsurface, but additionally can aid in determining orientations of principal stresses in the subsurface as described below.

Fractures in FWU caprock were described via the fracture class type, orientation, fracture dip, type of mineral fill, fracture porosity, fracture spacing, and intensity for Wells 13-14 and 32-8 [31]. For the Well 13-14 core, a detailed analysis of macroscopic fractures

was conducted on nearly 270 ft of continuous whole core material, approximately 123 ft of which contain significant fractures. For our purpose here, we focus on fracture data from Well 13-14 in the interval corresponding to the upper Morrow shale as it is the primary caprock lithology, and Well 13-14, being in the western portion of the FWU, is where the  $CO_2$  injection is being monitored by the SWP. Although the 13-14 core is unoriented, the coring-induced fracture orientations allow an estimation of core orientation with respect to principal stress orientations in the subsurface at FWU.

There are four types of fracture classes identified in the Well 13-14 core that include: Drilling or coring induced fractures; open low angle shear fractures; high-angle partially open fractures that heal through a carbonate interval; and filled fractures, generally a low angle. Drilling-induced fractures are the most abundant. Mineralized fractures are rare, but the most common mineral in-fill recognized is calcite. Rose diagrams indicating relative fracture orientation of all observed fractures in the Morrow shale were created for each fracture class and shown in Figure 8. The natural fractures in 13-14 show a similar orientation to the induced fractures and may indicate that the timing of the natural fractures to be more recent, i.e., formed under current stress orientations. According to the Snee and Zoback [38] stress map of Texas (see also [10]), the FWU should be located in a transitional stress state between a normal faulting regime and a strike-slip faulting regime where the maximum horizontal stress  $(S_H)$  is slightly less but approaching the vertical stress  $S_v$  in magnitude (i.e.,  $S_H \sim S_v > S_h$  where  $S_h$  is the minimum horizontal stress). The orientations of maximum horizontal stress in the Texas Panhandle, determined from horizontal breakouts, trend from SE-NW to EW, which would be the expected orientations of hydrofracture propagation, as well as open fractures (which open in a direction perpendicular to the least horizontal compressive stress direction).

If these orientations are indeed characteristic of natural fracture orientations at FWU, and if we understand the orientations of the principal stress directions, we can then determine critical dip directions for existing fractures that might be induced to slip upon pore pressure increases associated with injection. This is beyond the scope of the present chapter but will be addressed in a later work. However, the coincidence of the coring induced fractures and the natural fractures would suggest that these fractures would be of a critical orientation for slip (i.e., shear fracture) associated with fluid-injection induced overpressure. What works well for caprock integrity, however, is the relative rare occurrence of fractures overall in the FWU caprock lithologies as represented by core analysis.

#### 4.3.2. Static and Dynamic Geomechanical Behavior

It is important to understand the limiting strength of the shallow crust posed by existing fractures [37], and as well it is necessary to understand the heterogeneity in matrix rock mechanical properties. Static rock mechanics properties concern poro-elastic deformation, yielding, and ultimate rock strength and failure. A typical suite of rock mechanics tests that permit parameterization of constitutive models includes an unconfined compression (UCS) test (a right cylinder of rock is exposed to an axial load with no confining load applied to the round surface of the cylinder), several triaxial (TXC) tests at different confining pressures (an axial load is applied to the long axis of the cylinder with a constant confining pressure applied to the cylinder sides), and a hydrostatic test in which the rock cylinder is subject to a constant applied pressure, with or without the separately controlled pore pressure. A deformable jacket surrounding the cylinder keeps the pore and confining systems separate. These tests allow us to examine the variability of static elastic properties (i.e., Young's Modulus and Poisson's Ratio, which can either be used to represent an elastically isotropic medium or be directionally dependent, which is a simplified means to assess elastic anisotropy, for example, with respect to the primary bedding direction), yielding behavior (involving inelastic processes such as microfracture growth and coalescence or pore collapse), and failure (involving complete loss of cohesion of a deforming rock generally by a through-going shear fracture).



Mean 277.1°, Std. Dev. 17.2°

Mean 288.6°, Std. Dev. 33.0°

**Figure 8.** Strike rose diagrams for fractures observed in the Well 13-14 core for the Morrow shale (7660–7722 ft). (**A**) Coringinduced fractures; (**B**) all natural fractures; (**C**) open fractures; and (**D**) partially or totally mineralized fractures. The coincidence in directions between coring induced fractures and natural fractures existing at FWU suggests that the stress conditions resulting in the natural fractures were of similar orientation, and that natural fractures occurring in the FWU caprocks would be kept open under current subsurface stress conditions.

An extensive suite of geomechanical properties have been assembled from the Terra Tek testing program for the FWU characterization wells [31]. One valuable aspect of the data set is the degree to which it maps properties on rock units based on Terra Tek's HRA methodology for sampling and testing. We focus here on elastic properties, failure envelopes, and fracture gradients as they concern sealing lithology responses to fluid injection.

Static and dynamic elastic properties are represented as continuous profiles that combine well logging, Terra Tek's HRA analysis, and laboratory measurements on the core that is used for calibration. These are presented in Figures S4–S6 in the Supplementary Materials. The results for the eleven HRA rock classes for well 13-10A are summarized in Figure 9.



**Figure 9.** Static Young's Modulus (**A**) and Poisson's Ratio (**B**) determined by combining ranges interpreted from well log static rock compression tests illustrating the contrast in elastic properties of the Morrow B sandstone reservoir and the Morrow shale and Thirteen Finger Limestone caprock for Well 13-10A. The left-hand figures show values for samples oriented horizontally, and the right figures show values for samples oriented vertically. In general, horizontal values are slightly higher than vertical values, reflecting an anisotropy likely derived from depositional fabrics.

In general, horizontal values are slightly higher than vertical values, reflecting an anisotropy likely derived from depositional fabrics. The highest values (with light blue) are found in the Thirteen Finger limestone cementstones, the next highest correspond to the black color (Bcm facies in the Thirteen Finger limestone), whereas the lowest values (orange and grey) are weaker Bcm lithofacies in the Thirteen Finger limestone. Morrow B sandstone lithofacies (dark blue) and Morrow shale (yellow, red, and brown) lithofacies are intermediate in value. In general, this is not an unexpected degree of elastic heterogeneity, but could influence how the caprock responds to a reservoir-scale increase in pore pressure associated with CCUS activities.

Of greater interest for caprock integrity is the failure behavior of the suite of relevant rock types, and these are presented as failure envelopes in Figure S7 in Supplementary Materials. Due to core recovery issues, the triaxial testing results are limited to the more competent lithofacies, whereas for caprock integrity, the weaker lithofacies which were not recovered or were otherwise damaged during coring are of greater interest as these lithologies would represent the greater threat to sealing integrity from fluid injection and over-pressuring. However, the results of the triaxial testing were useful as calibrations for well log data in a proprietary approach by Terra Tek to estimate fracture gradients. Figure S7 shows Coulomb failure envelopes for Thirteen Finger limestone and Morrow shale caprock and Morrow B sandstones created by combining UCS and triaxial test data for these rock types. As discussed by Trujillo [10], Morrow B sandstones are much weaker with much lower cohesion than the mudstone or limestone lithofacies in the upper Morrow shale or the Thirteen Finger limestone.

## 4.3.3. Fracture Gradients in Farnsworth Reservoir and Sealing Lithologies

We bracketed the orientation of the three principal stresses within the FWU from regional observations [38], which may correspond to directions of open and induced fractures in the upper Morrow shale. There is a vertical maximum principal stress, a minimum horizontal stress in the orientation of 350° (North-South), and a maximum

horizontal stress orientation at about 270° (East-West). A more difficult determination is an assessment of magnitude of the principal stresses (vertical/overburden stress,  $S_v$ , the maximum horizontal stress,  $S_H$ , and the minimum horizontal stress,  $S_h$ ), and addressing this is beyond the scope of this paper. However, based on the rock mechanics testing data and the Terra Tek analysis (summarized in Figures S4–S6 in the Supplementary Materials), we can bracket the minimum horizontal stress gradient required to exceed rock strength and propagate fractures. These estimates are typically used to limit the extent of injectionassociated pore fluid overpressures so as to not damage formations during injection and production activities. For CCUS in the FWU, these values are important to consider. Based on the in situ stress orientations in the FWU, any fractures created in the weaker reservoir lithology would be oriented vertically (for joints or tension fractures) or steeply dipping (in the case of shear fractures), given the orientations of the least principal stresses.

Estimates of the minimum horizontal stress gradient in FWU caprock and reservoir lithologies are determined from the Terra Tek suite of testing shown in Figures S4–S6 and are summarized in Figure 10 for all three characterization wells. The lowest values are in the well 13-14, but in general values cluster around 0.70 to 0.80 psi/ft (1 psi/ft is equivalent to 0.0226 MPa/m). Although some of the lowest values are in the caprock lithologies, so are the highest values, with the Morrow B sandstones falling generally below 0.75 psi/ft. Pore pressure gradients range from 0.43 psi/ft in the Thirteen Finger limestone and increase to 0.585 psi/ft in the upper Morrow shale [10], while an estimated vertical stress gradient is 1.1 psi/ft. With a fracture gradient of 0.7 psi/ft at a depth of 7700 ft (2347 m) in the reservoir, the maximum pore pressure that could be attained within the reservoir without fracture is ~5390 psi or ~37 MPa. At the caprock-reservoir interface the fracture gradient is 0.85 psi/ft at a depth of 7668 ft (2337 m), the maximum pore pressure that could be attained within the caprock without fracture is ~6518 psi (~44.9 MPa). Injection-induced pressures by the  $CO_2$  in the western portion of the field are on the order of 5000 psi (34.5 MPa), which is below the maximum level. The fracture gradients indicate that the Morrow B sandstone reservoir is weaker than the overlying lithologies, so any fracture initiated around CCUS injection wells in the FWU should not propagate into the overlying sealing units.

#### 4.4. Seal Continuity across the Farnsworth Unit

Isopach maps of the upper Morrow shale and Thirteen Finger limestone across the FWU were prepared from formation tops and bottoms after data compiled by [9] and are shown in Figure S8 in the Supplementary Materials, along with the total caprock thickness. The minimum thickness for the upper Morrow shale occurs in the middle of the FWU at ~42 ft (12.8 m). The minimum thickness of the Thirteen Finger limestone occurs in the western portion of the FWU at around 60 ft (18.3 m). In general, the caprock thickness ranges from 240 ft (73.2) in the eastern portion to ~120 ft (36.6 m) in the western portion of the FWU. The lateral caprock continuity easily suggests that seal integrity would be anticipated along the mapped extent of the FWU.

## 4.5. Seal Integrity Inferred from Noble Gas Analyses

Measurement of naturally occurring noble gases in a vertical profile from the preserved fresh core in the reservoir and caprock units complements the other caprock integrity analyses as the pattern of noble gas isotopic content is the direct in situ integrated result of the driving forces and transport properties through the reservoir and the caprock. Thus, the noble gas isotopic profile reflects the original infiltration of groundwater with atmospheric noble gas contents and the addition of subsurface geogenic noble gases, which are affected by transport via advection and/or diffusion and potentially more recent reservoir activities since FWU water flooding began in the 1950s. Noble gas profiles that reflect diffusion-dominated transport are expected for high sealing quality caprock, whereas caprock with seal bypass systems (i.e., an interconnected fracture network) may result in an advective noble gas profile [7].



**Figure 10.** Estimated minimum horizontal stress (fracture) gradients by rock class for each of the three characterization wells. In general, the Morrow B sandstone rock classes (light and dark blue) have lower values indicating they are more easily fractured. Propagating vertical fractures associated with injection-induced hydrofracturing would likely not propagate into the overlying caprock formations.

The context for interpreting noble gas data measured in this study is that atmospherically sourced isotopes are <sup>20</sup>Ne and <sup>36</sup>Ar, whereas geogenic isotopes sourced in the subsurface are <sup>3</sup>He, <sup>4</sup>He, <sup>40</sup>Ar, and <sup>22</sup>Ne [39]. Isotopic ratios for atmospheric, crustal, and mantle reservoirs are well known and used to identify sources of fluids in petroleum systems [40]. The measured <sup>3</sup>He over <sup>4</sup>He ratio (R) from FWU samples, normalized by that same ratio for the atmosphere ( $R_a$ ), have values of ~0.02 for most measurements within the Thirteen Finger limestone and the upper Morrow shale (Figure 11, see the left-most column; values are listed in Table S7 in the Supplementary Materials). These values of ~0.02 are consistent with crustal fluids—the crustal end-member  $R/R_a$  value is 0.02, which represents the dominant production of <sup>4</sup>He from U and Th decay [40]. Deviations from values of ~0.02 occur within the Morrow B sandstone and near the top of the Thirteen Finger Formation (Figure 11).

The Morrow B sandstone deviations from 0.02 R/R<sub>a</sub> are most likely caused by the long-term water flooding in the Farnsworth Unit, which initially used groundwater sourced from the Miocene Ogallala Formation in the Texas, USA, Panhandle that probably had R/R<sub>a</sub> values at closer to 1.00 than the older caprock fluids (younger groundwaters will probably have values closer to one than the older crustal fluids; see [40]). The R/R<sub>a</sub> value greater than 1.00 in the Morrow B sandstone may be an artifact of the laboratory analysis. Mantle-sourced fluids have R/Ra values much greater than one [40], but this is unlikely as a source due to the rest of the samples being less than one. Complex phase partitioning between groundwater, oil, and any gas phase may also lead to ratios greater than one. Ratios of <sup>4</sup>He/<sup>20</sup>Ne, normalized by the atmospheric value, are several orders of magnitude greater than one for most samples, thus indicating high helium concentrations due to the long-term production of <sup>4</sup>He from U and Th in the sealing lithologies with low permeability and low effective diffusivity. The very distinct change in R/R<sub>a</sub> from the Morrow B into the upper Morrow shale indicates that the upper Morrow shale is a good seal at least at that contact measured by the coring.

Due to the high amount of methane and helium in many samples as observed during the laboratory analysis, sample splitting was necessary, which affected the reliability of the argon values. Thus, argon values were not reported by the laboratory for several samples (Table S7). The argon isotopic values that are available also reflect some processes that introduce fluids into the system that may have been in equilibrium with the atmosphere (Figure 11). A sample within the upper Morrow shale has a relatively low light-to-heavy Ar isotopic ratio, which is expected as <sup>40</sup>K within the formation would produce <sup>40</sup>Ar.

The deviations from  $0.02 \text{ R/R}_{a}$  for the Thirteen Finger limestone may be due to the improper sealing or leakage of the preservation canisters, as such leakage would bring the values closer to 1.00, which may be likely for the sample at depth 7515 ft (2290.57 m) as its  $R/R_a$  is 0.47, and its neon and argon isotope ratios are close to the atmospheric values (Figure 11). However, the adjacent sample at depth 7502 (2286.01 m) also has a relatively high  $R/R_a$  of 0.034 and its neon and argon ratios are slightly shifted from the atmospheric equilibrium values. Thus, it is possible that some process occurs near the top of the Thirteen Finger limestone to introduce a minor atmospheric source of (meteoric) fluids or is otherwise fractionating the noble gases. We speculate that the observed natural fractures may permit fluid movement that has larger  $R/R_a$  than the crustal values of ~0.02 of the rest of the Thirteen Finger limestone and upper Morrow shale samples. This would suggest that although the upper Morrow shale and lower Thirteen Finger limestone appear to have been isolated from the surrounding fluid movement (and fluid contamination associated with decades-long water flooding operations at FWU), the upper portions of the Thirteen Finger limestone may have been infiltrated by fluids in contact with atmospheric noble gas isotopic values.



**Figure 11.** Noble gas ratios versus depth for Well 13-10A. The subscript *m* stands for the ratio measured for the sample, whereas the subscript *ASW* stands for the air saturated water value for the ratio.

#### 5. Discussion

Direct formation-scale assessment of caprock integrity is difficult in a large part from the heterogeneity at all scales. Wire-line logging and seismic techniques may lack resolution to identify potential seal-by systems (e.g., such as connected fracture networks that are below seismic resolution). Assessments of capillary heterogeneity and geomechanical behavior from small-scale core-plug measurements may not be representative of heterogeneity across formation scales and can reflect a sampling bias from the core recovery. However, both methods are used to infer large-scale behavior, which may include modeling to integrate to the reservoir and caprock properties made at different locations and different scales [41]. To build confidence in and understanding of caprock integrity at FWU, this study approaches caprock integrity by systematically assessing processes that govern the sealing quality at different scales following the framework of Figure 1. Thus, the processes are examined from nanoscale capillary-wettability controls to mechanical properties and the full caprock-reservoir system behavior via sedimentological-stratigraphic evaluation and large-scale in situ noble gas transport. Small-scale sealing integrity is confirmed by MICP measurements of high breakthrough pressures and very high estimated CO<sub>2</sub> column heights for the upper Morrow shale and the Thirteen Finger limestone. Mechanical properties from core measurements indicate that, as the Morrow B sandstone is relatively weak, fractures that may be induced from CO<sub>2</sub> injection activities would probably not propagate into the upper Morrow shale. The naturally occurring in situ noble gas isotopic profile

builds confidence that water flooding and production reservoir operations prior to coring of Well 13-10A did not damage a high-quality sealing caprock as the helium ratios are quite different across the Morrow B sandstone and upper Morrow shale contact. The thickness and lateral continuity of the upper Morrow shale and Thirteen Finger limestone further strengthen the argument for a high-quality sealing caprock system at FWU.

# 6. Conclusions

Our main conclusions from this study are drawn from the five topics in the Results Section and are as follows:

- A cluster analysis of rock heterogeneity based on well log and other analyses by Terra Tek shows that the caprock lithologies at FWU can be grouped into nine separate units. This classification forms the basis for subsampling and core plug analysis (when possible), as well as determinations of static and dynamic rock mechanics properties and fracture gradients.
- MICP results show that sealing units in the Morrow shale and Thirteen Finger limestone units should provide excellent sealing capacity for storage of CO<sub>2</sub> in the Morrow B Sandstone injection unit, as calculated CO<sub>2</sub> column heights exceed the thickness of the Morrow B. Cementstones in the Thirteen Finger limestone have anomalously high sealing potential and strength, and the ability of these thin bands of tight carbonate to serve as seals by themselves would be limited only by their lateral continuity.
- An assessment of fracture gradient across the reservoir and caprock lithologies is drawn from the HRA, well log analysis, and laboratory triaxial testing. The range of fracture gradients show that formations should be able to support a relatively large injection-induced overpressure to around 7 or so MPa (~a thousand psi) over hydrostatic pressure values at the depths of interest. Existing fractures are apparently rare in the FWU caprocks but may have orientations that suggest creation under existing stress conditions at FWU, given the similarity in orientations to coring-induced fractures. Failure analyses show that the Morrow B sands are weaker than overlying lithologies, so that any fracture initiation around the injection well would not be expected to propagate into the overlying sealing units.
- Caprock units including the upper Morrow shale and Thirteen Finger limestone show sufficient thickness and lateral continuity across the FWU suggesting good sealing potential, barring any significant seal by-pass features.
- The noble gas analysis from fresh core shows that the caprock lithologies show no degree of leakage from historical water and CO<sub>2</sub> flooding in the FWU, whereas the Morrow B sandstone shows an impact from historical EOR activities. The upper Thirteen Finger limestone contains noble gas values that are consistent with invasion by meteoric waters, whereas the middle and lower Thirteen Finger limestone and upper Morrow B shale contain values that suggest hydrologic isolation.

Together, these analyses conducted at different scales strongly suggest an excellent sealing capacity for the Morrow shale and Thirteen Finger limestone lithologies. This is ascertained from the high degree of capillary sealing, the low potential for seal bypass, and the large regional extent of the caprock lithologies in the FWU.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10 .3390/en14185824/s1, Tables S1–S3: Caprock thin section petrologic descriptors with Schlumberger Heterogeneous Rock Classification (HRA) assigned unit color; Table S4: Summary of petrophysical properties (Terra Tek routine core analysis); Table S5: Terra Tek tight rock analysis for mudstone and limestone lithofacies in the Morrow shale and Thirteen Finger limestone; Table S6: Mercury intrusion data and associated analysis by rock class for the 13-10A, 13-14, and 32-8 characterization wells; Table S7: Results of noble gas analysis, including the sample mass and supplementary estimates of wet bulk density, total porosity based on laboratory analysis on fresh core samples or well log interpretation; Figure S1: Well 13-14 HRA summary and accompanying well logs used in the analysis; prepared by Schlumberger; Figure S2: Well 32-8 HRA summary and accompanying well logs used in the analysis, prepared by Schlumberger; Figure S3: Pore throat diameter in microns vs. incremental non-wetting phase saturation by formation and well location, from mercury porosimetry measurements; Figure S4: Well 13-10A interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots); Figure S5: Well 13-14 interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots); Figure S6: Well 32-8 interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots); Figure S6: Well 32-8 interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots); Figure S7: Coulomb failure envelopes for representative caprock lithologies from triaxial core testing; Figure S8: Isopach maps of caprock lithologies in the Farnsworth Unit. A. Morrow shale; B. Thirteen Finger limestone; C. Total caprock thickness (after Rose-Coss 2017, [9]).

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Conflicts of Interest: The authors declare no conflict of interest.

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