Supplemental Material

The following materials supplement the data, figures, and presentation given in the manuscript "Multiscale Assessment of Caprock Integrity…" by Trujillo et al. These include the following tables and figures, presented in the order of referencing in the main text:

Tables:

Table S1 through Table S3 contain brief petrologic descriptions obtained from thin section observation by Steve Cather (Personal Communication, 2018) of the New Mexico Bureau of Geology and Mineral Resources, New Mexico, USA, of samples from wells 13-10A, 13-14, and 32-8 of the Farnsworth Unit (FWU) in West Texas, USA. These description form part of the basis of mapping the Schlumberger Heterogeneous Rock Analysis (HRA) lithological indicators (using a proprietary algorithm based on combining well log and caliper responses with rock mechanics laboratory testing results) to core-scale observations of rock properties. These tables include depth of thin section sampling, a brief description of texture, mineralogical content, fossil content, etc., the formation sampled, and the HRA classification associated with the sampling depth and descriptor.

Table S4 contains a summary of measurements of petrophysical properties of 2.54 cm (1″) diameter x nominally 5.0 cm (2″) length core plugs from Wells 13-14 and 32-8, performed by Schlumberger (formerly Terra Tek of Salt Lake City, USA), after Rose-Coss et al. (2017) [9]. The table includes depth of sampling, HRA classification, sample dimensions, dry bulk and grain densities, porosity measured at ambient conditions, water and oil saturation, and N_2 gas permeability under ambient stress conditions. Measurements and data from core plugs from Well 13-10A are given in Appendix A, Table 1 of Rasmussen et al. (2019) [2] and not repeated here. The HRA Rock Class assignments for Well 13-10A samples are not given in the Rasmussen et al. (2019) [2] appendix but are dominantly from the Morrow-B unit and thus are assigned the "Dark Blue" classification, as shown in Figure 4 of the main text.

Table S5 contains a summary of measurements of caprock core samples from the Thirteen Finger limestone and Morrow shales from the FWU characterization wells 13-10A, 13-14, and 32-8 obtained using the Schlumberger (formerly Terra Tek) proprietary Tight Rock Analysis. These lithofacies typically have poor core recovery and exhibit both difficulty in standard core plugging and core testing methodologies compared to the samples in Table S4. The table includes the sample ID; the HRA Rock Class Assignment; interpreted lithofacies by Rose-Coss et al. (2017) [9]; depth of sampling; measured dry bulk and grain densities; gas-filled, hydrocarbon-filled, and total porosities; water, gas and oil saturations; and pressure-decay permeability. A few listed samples had permeabilities above the range of the pressure decay method and instead were tested at listed stress conditions via Terra Tek's pulse decay method.

Table S6 contains results of mercury intrusion capillary pressure (MICP) porosimetry performed by Micromeritics, Inc. of Houston, TX, USA on 2.54 cm (1″) diameter core plugs of reservoir and caprock lithofacies from wells 13-10A, 13-14, and 32-8. Core plugs were difficult to obtain from caprock lithofacies (from Thirteen Finger limestone and Morrow shale units) and so these measurements reflect a sampling bias of the more "core-able" lithologies. Selected reservoir core plugs underwent a cleaning via a toluene extraction method, and these are designated in the table by a 'Y' in the "Cleaning" column. Included in the table are the Terra Tek sampling ID, the HRA Rock Classification Assignment, the depth of sampling, the core plug orientation with respect the coring direction ('h' refers to horizontal and 'v' refers to vertical), whether the core plug was cleaned of hydrocarbons ('y' refers to yes or cleaned and 'n' refers to no or not cleaned), the calculated breakthrough pressure of mercury during flooding, the calculated CO_2 column heights inferred to be supported by the measured capillary properties of the core plugs (see Methods

section in the main text), the calculated permeability from the MICP results, and the calculated breakthrough or limiting pore-throat diameter.

Table S7 includes results of noble gas measurements from caprock lithologies from Well 13-10A of the FWU, performed by Dr. Solomon's laboratory at the University of Utah, USA on preserved core samples. The table includes depth of sampling referred to the measured core depths; the sample mass; the measured as-is wet bulk density and total porosity; He and Ar isotopic contents; and relevant isotopic ratios.

Figures:

Figures S1 and S2 depict the Heterogeneous Rock Analysis (HRA) log prepared by Schlumberger using proprietary algorithm, for wells 13-14 and 32-8, to accompany Figure 4 in the main text (for Well 13-10A), which depicts well log and caliper results for FWU characterization wells [31]. The logs include logging depth (in feet); depth of core (note some discrepancies with the logging depth) in feet; the whole core intervals extracted, shown in black; the inferred formation/unit tops; measured gamma ray and caliper logs; measured resistivity logs; porosity and lithology indicator logs (using a method proprietary to Schlumberger); the assigned HRA rock classification by color which includes eleven separate rock classes (two for the Morrow-B reservoir and nine for the caprock lithologies); estimations of the error in the HRA designation as assigned by Schlumberger; the core total gamma ray count; and the calculated core uranium, thorium, and potassium contents inferred using a proprietary method by Schlumberger.

Figure S3 summarizes mercury porosimetry results for the Morrow-B reservoir sandstone, and the upper Morrow shale and Thirteen Finger limestone caprocks.

Figures S4, S5, and S6 give results of the Schlumberger completion quality logs for wells 13-10A, 13-14, and 32-8 [31]. Along with the same log and core depths, completion intervals, gamma ray and caliper logs, and assigned HRA classification (shown in Figure 4 in the main text and figures S1 and S2 given here), these include calculated static and dynamic Young's Modulus and Poisson's Ratio, P- (compressional) and S- (shear) wave velocities, calculated minimum horizontal stress, and inferred fracture width. These data are presented as continuous curves and are compared to laboratory measurements given by the circles. Associated errors with these calculations are given in the "CQL-Error" column where the grey shading shows intervals with higher uncertainty. The calculated minimum horizontal stress and stress gradient are calculated using Schlumberger proprietary modeling assuming a pore pressure gradient ranging from 0.52 to 0.59 psi/ft (0.012 to 0.013 MPa/m respectively) and an overburden stress gradient of 1.08 psi/ft (0.024 MPa/m). The fractured width column depicts a relative ease of fracturing rock at a given depth, where wider widths are associated with lower fracture breakdown pressures and narrower widths associated with higher breakdown pressures.

Figure S7 give results of triaxial testing of reservoir and caprock core samples, in the form of Coulomb failure criteria [31]. The upper Morrow shale and Thirteen Finger limestone caprock lithologies are much stronger than the Morrow-B reservoir sandstone at FWU.

Figure S8 (after Rose-Coss, 2017, [9]) are isopach maps of the thickness of each of the caprock lithologies and the total thickness of caprock at the FWU.

Table S1. Well 13-10A caprock thin section petrologic descriptors with Schlumberger Heterogeneous Rock Classification (HRA) assigned unit color.

Depth (m)	Description	Formation	Class
2293.97	Slightly fossiliferous, burrowed dolomite or dedolomite. Areas between burrows are organic-rich. A few intraclasts are present. No visible porosity.	Thirteen Finger limestone	Light Blue
2298.39	Slightly fossiliferous micritic and sparitic limestone with scattered dolomite rhombs. Dolomite crystals are 0.03–0.06 mm; micrite is brownish due to organic content. About half of thin the section is composed of a bed of organic-poor sparry calcite. No porosity is visible except for in one partly plugged natural fracture	Thirteen Finger limestone	Light Blue
2299.40	Organic-rich, fossiliferous, dolomitic claystone. No visible porosity.	Thirteen Finger limestone	Orange
2299.87	Slightly fossiliferous dedolomite or dolomitized micrite. No visible porosity.	Thirteen Finger limestone	Light Blue
2318.18	Fossiliferous, organic-rich marine claystone. Exhibits numerous burrows containing fossil shell hash (foraminifera, ostracods, brachiopods, and thin-shelled pelecypods). No visible porosity.	Thirteen Finger limestone	Black
2319.73	Fossiliferous, organic-rich marine claystone. Exhibits numerous burrows containing fossil shell hash (foraminifera, ostracods, brachiopods, and thin-shelled pelecypods). No visible porosity.	upper Morrow shale	Black
2320.19	Coal. Contains thin layers and lenses of mudstone. Very low porosity.	upper Morrow shale	Olive
2326.43	Fossiliferous, organic-rich mudstone. Contains minor quartz/feldspar silt and scattered microspar.	upper Morrow shale	Brown
2326.77	Slightly fossiliferous, organic-rich, slightly calcareous mudstone. Contains scattered quartz, feldspar, muscovite and calcareous fossil-hash silt. No visible porosity.	upper Morrow shale	Brown
2329.42	Fissile, slightly fossiliferous, organic-rich mudstone. Contains common silt (quartz, feldspar, muscovite) and minor microspar(?). No visible porosity.	upper Morrow shale	Brown
2333.09	Slightly silty claystone. Contains minor quartz/muscovite/feldspar silt and many faint burrows. Claystone exhibits yellow birefringence, so probably consists of illite, smectite, and/or chlorite. No visible porosity.	upper Morrow shale	Yellow
2334.23	Burrowed silty claystone. Contains significant quartz/muscovite /feldspar silt. Claystone exhibits yellow birefringence, so probably consists of illite, smectite, and/or chlorite. No visible porosity.	upper Morrow shale	Yellow
2351.92	Laminated mudstone. Contains a few quartz/muscovite/feldspar silt layers. Clays exhibit yellow birefringence, so probably consist of illite, smectite, and/or chlorite. No visible porosity.	upper Morrow shale	Red

Table S2. Well 13-14 caprock thin section petrologic descriptors with Schlumberger Heterogeneous Rock Classification (HRA) assigned unit color.

Depth (m)	Description	Formation	Class
2026.37	Micritic CO3, Has minor terrigenous silt, lots of fine fossil hash. Marine. Fractures are all late or man-made. Very uniform texture.	Thirteen Finger limestone	Brown
2028.20	- Biosparite w/lots of marine fossils. Local layers of organic-rich micrite. Minor intra-fossil porosity, otherwise tight. NO fractures. Loose packing -> early spar.	Thirteen Finger limestone	Brown

2028.50	Same as above except moderate packing, no micrite. No fractures. Terrigenous grains are sand-sized. Closer to shore?	Thirteen Finger limestone	Brown
2032.83	Sandy biosparite/biomicrosparite. Much sand-sized quartz and feldspar. Many marine fossils. A few hairline, late fracture (possibly man-made?)	Thirteen Finger limestone	Light Blue
2034.71	Spar-cemented sandy biosparite (10 -15% of T.S.) Sand is fine, average ~ 0.2 mm, mostly quartz and feldspar. CO3 grains are mostly various marine fossils w/few peloids/coated grains. Spar cement. A few thin fractures, probably all man-made. Very low porosity, only a few scattered, dissolved fossil fragments (aragonite?). A few glauconite grains.	Thirteen Finger limestone	Light Blue
2035.18	Spar-cemented sandy (~10%) biosparite. Same as above but has more glauconite grains. Very low porosity, no natural fractures. Somewhat coarser-grained than above.	Thirteen Finger limestone	Light Blue
2038.45	Spar-cemented sandy (~10%) biosparite. Same as 6677.09.	Thirteen Finger limestone	Light Blue
2040.50	Spar-cemented sandy (~30-40%) biosparite. Quartz/feldspar sand subequal to CO3 grains (mostly fossil fragments) Sand is coarser than above, (~0.3mm) About 1/3 of t.s. is splits of organic-rich mudstone with yellow clay (illite/smectite) and quartz, feldspar, and minor muscovite silt. Mudstone may be calcareous. Possibly nearer to shore than above three thin sections. No natural fractures, very low porosity.	Thirteen Finger limestone	Light Blue & Black
2044.03	- Interlaminated siltstone and organic-rich silty claystone. Silt is quartz, feldspar, and muscovite. Clay is yellowish (illite/smectite). Some organics organized into very thin discontinuous laminae (coal seams?_). Coaly plant fragments ~ 0.015 mm thick. No natural fractures. No porosity in mudstone, slight porosity in siltstones and intergranular microporosity within clay cement matrix.	Thirteen Finger limestone	Black
2045.38	Coarse biosparite - fossil fragments (~0.6 mm average, mostly crinoid echinoid fragments ->single crystals). Cool Thin section. No siliciclastics. Clean, high energy CO3. No porosity except very few partly dissolved aragonite (?) fossils. No fractures. Well sorted.	Thirteen Finger limestone	Light Blue
2046.45	Slightly fossiliferous laminated, organic-rich dolomite or dedolomite (dedolo). Dolo/dedolo crystals are about 0.02 mm in micrite matrix. No fractures, no porosity.	Thirteen Finger limestone	Light Blue
2050.88	Burrowed neomorphic (?) sparite/ microsparite (~10-30 um) Very few fossils and quartz/feldspar silt. No porosity except remnant within bitumen-filled fractures.	Thirteen Finger limestone	Light Blue

2318.42	Dolomite or dedolo with rare fossil fragments and pellets. Dolomite is ~20 um size. No siliciclastics, no porosity. Most fractures are man-made except a few around the periphery that are filled completely with bitumen.	Thirteen Finger limestone	Light Blue
2321.13	Dark, organic-rich slightly silty claystone. No carbonate, Silt is quartz/feldspar mix. Cannot tell for sure about clays - possibly illite/smectite. No porosity, no natural fractures.	Thirteen Finger limestone	Grey
2329.04	Burrowed biomicrite. Lots of fossil fragments, some are phosphatic. Spar is locally present (neomorphic?). Poorly sorted, no dolomite or silt, no porosity or natural fractures.	Thirteen Finger limestone	Brown
2332.12	Burrowed biomicrite. Lots of fossil fragments, some coated grains. no porosity or natural fractures.	Thirteen Finger limestone	Brown
2332.54	Organic-rich silty mudstone. Silt is quartz/feldspar mix, ~40 um. Organics are disseminated and occur as thin seams, probably plant fragments. Numerous hair-line fractures are filled or partly filled with bitumen, otherwise, no porosity.	upper Morrow shale	Orange
2341.70	Laminated organic-rich claystone with minor very fine silt. Yellowish birefringent clays. Numerous organic-rich partings; most are plant fragments but some may be bitumen-filled fractures that are parallel to bedding (SC doubts but is possible). No porosity, no burrows.	upper Morrow shale	Orange
2343.26	Moderately burrowed claystone. Has a few percent quartz/feldspar fine silt. Moderate organics. Has several hairline fractures, partly to completely filled with bitumen, oblique to bedding, and yellowish birefringent clays.	upper Morrow shale	Purple
2345.22	- Sandy mudstone. Sand is as coarse as 0.5 mm and grades down to silt (quartz/feldspar/muscovite). Clays have yellowish birefringence. Several thin fractures are partly to completely filled with bitumen. Weak intergranular microporosity within clayey areas are common.	upper Morrow shale	Yellow

Table S3. Well 32-8 caprock thin section petrologic descriptors with Schlumberger Heterogeneous Rock Classification (HRA) assigned unit color.

Depth (m)	Description	Formation	Rock Class
2379.85	Dark organic-rich calcareous mudstone. Laminated. Scattered very thin bivalves look like CO3-filled fractures, but are not - they are fossils. Clay birefringence is uncertain due to organics. Rare fine quartz/feldspar silt scattered throughout. No natural fractures or visible porosity.	Thirteen Finger limestone	Orange
2382.89	Organic-rich Micritic limestone, partly neomorphosed to microspar. No quartz/feldspar silt, no visible porosity. Numerous hairline fractures of various orientations are lined with bituminous material. Some fractures are en echelon;	Thirteen Finger limestone	Light blue

	some are cross-cutting, and none have visible porosity. Cross-cutting relationships suggest subhorizontal fractures are younger than vertical.		
2402.75	Same as 7807.9 except slightly more (a few %) quartz/feldspar fine silt grains. No natural fractures, no visible porosity. Well laminated.	Thirteen Finger limestone	Orange
2391.35	Same as above except less well laminated. No natural fractures, no visible porosity.	Thirteen Finger limestone	Orange
2394.43	Slightly fossiliferous, organic-rich muddy Micritic limestone. Weakly laminated. No quartz/feldspar silt, no natural fractures, no visible porosity.	Thirteen Finger limestone	Light blue
2397.19	Fossiliferous, moderately organic-rich dolostone or de-dolostone. Carbonate is locally rhombic, so probably dolomite or de-dolomite. Weakly laminated, no natural fractures, no visible porosity.	Thirteen Finger limestone	Grey
2409.65	Well-laminated organic-rich mudstone with a few percent of quartz/feldspar silt. Has a Micritic parting but otherwise is mostly siliciclastics. Only slightly fossiliferous. No natural fractures, no visible porosity.	upper Morrow shale	Yellow
2412.50	Mudstone with numerous laminae of silt and very fine sand. Much coaly plant fragments along bedding surfaces. Clays have yellow birefringence thus are probably illite or smectite. Local areas with diagenetic pyrite and associated gypsum (?) in vugs. no natural fractures, no visible porosity.	upper Morrow shale	**Brown**
2418.54	Sandy mudstone. Sand grains are ~0.15 mm, floating in yellowish clay (illite/smectite). Lots of bedding-parallel fractures, but none obviously natural. Very low porosity.	upper Morrow shale	Purple
2424.99	(probe) - Micrite with numerous floating spherulitic carbonate blebs ~0.2-0.4 mm diameter. These are subspherical, well sorted, bimineralic (both carbonate but outer rim is reddish). Weird rock. Some rare, scattered quartz/feldspar silt. No porosity except minor microporosity associated with reddish rim on spherules and minor occurrences in micrite matrix. No natural fractures.	Morrow-B sandstone	Green
2437.26	Dolomite or de-dolomite (0.1 mm) with scattered rare quartz/feldspar silt and mudstone intraclasts. Faintly burrowed. A few kerogen-rich streaks. No natural fractures, no visible porosity.	lower Morrow shale	Light blue
2440.67	Moderately organic-rich laminated claystone with rare scattered quartz/feldspar silt. Local organic-rich partings and laminae, some of which are intersected by man-made fractures. No visible porosity clays are mostly yellowish birefringence so illite or smectite. No natural fractures.	lower Morrow shale	Yellow

2447.21	Organic-rich laminated claystone with local silty partings. No visible porosity, no natural fractures. Clays are dominantly illite or smectite.	lower Morrow shale	Orange

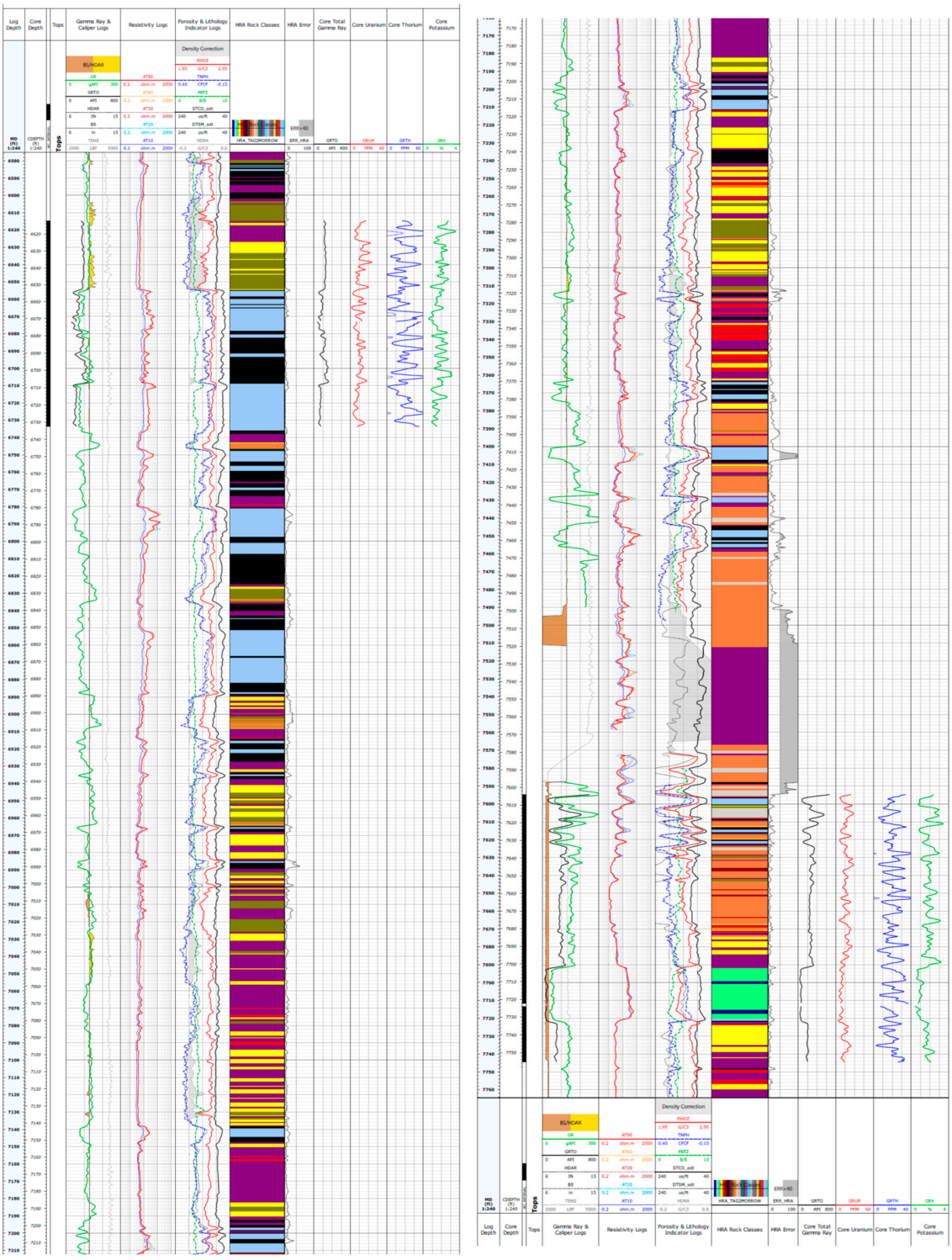

Figure S1. Well 13-14 HRA summary and accompanying well logs used in analysis; prepared by Schlumberger.

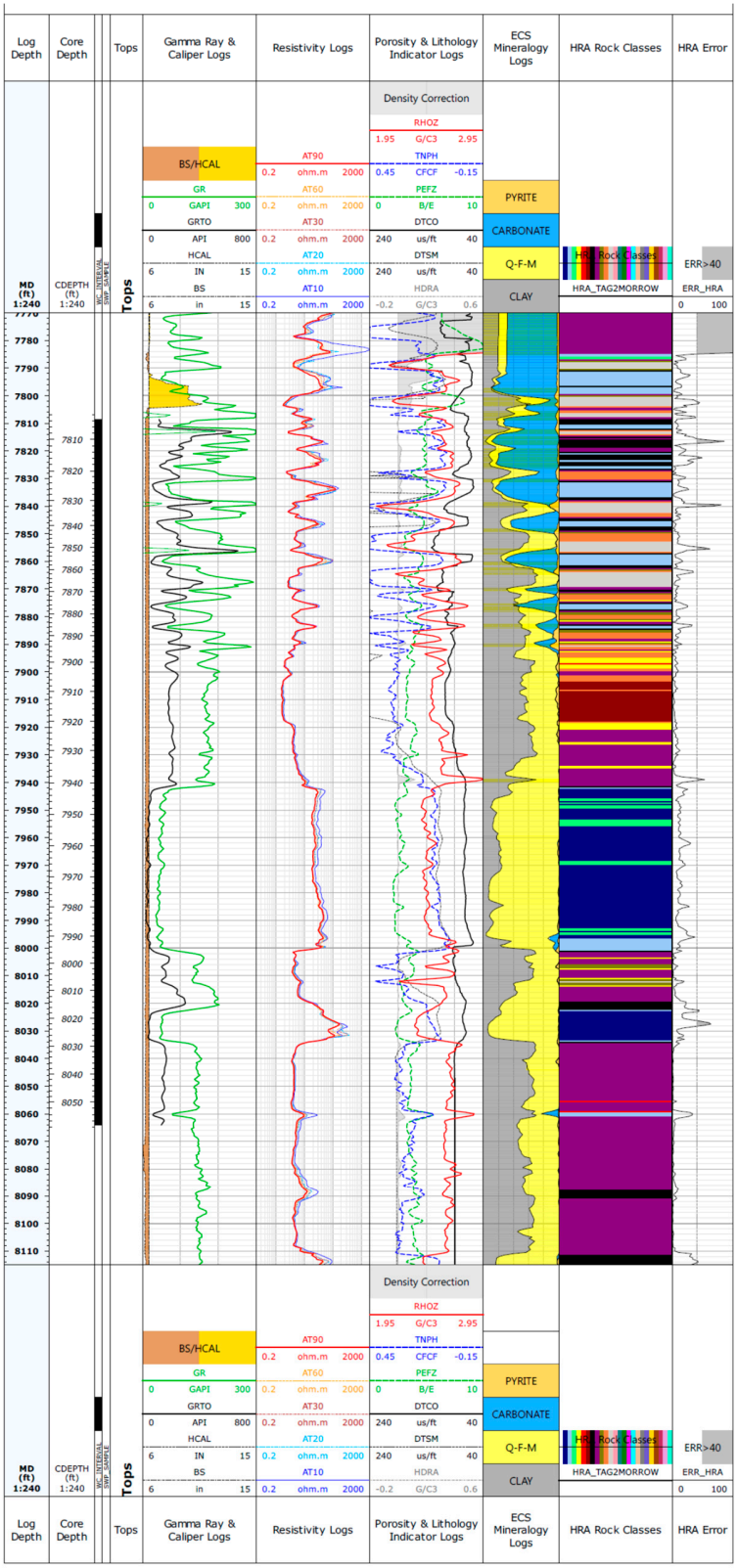

Figure S2. Well 32-8 HRA summary and accompanying well logs used in analysis; prepared by Schlumberger.

Table S4. Summary of petrophysical properties (Terra Tek routine core analysis)

Sample ID	HRA Rock Class	Depth (m)	Sample Length (cm)	Sample Diameter (cm)	Dry Bulk Density (g/cc)	Grain Density (g/cc)	Ambient Porosity (%)	Water Saturation (%)	Oil Saturation (%)	Gas Perm. NOB Stress (mD)
Well 13-14										
12	Purple	2347.4	3.89	2.53	2.312	2.719	14.99	32.97	13.99	0.50
13	Green	2348.3	3.91	2.53	2.147	2.710	20.79	20.21	23.69	3.53
14	Green	2349.4	3.84	2.54	2.156	2.669	19.22	29.47	23.04	100.7
15	Dk Blue	2350.1	3.95	2.53	2.206	2.720	18.91	18.12	20.41	24.58
16	Green	2351.0	3.88	2.53	2.243	2.664	15.80	16.77	18.35	2.98
17	Green	2351.9	3.95	2.53	2.147	2.653	19.10	23.64	19.82	7.17
18	Green	2352.9	3.85	2.53	2.230	2.668	16.42	24.55	17.26	5.13
19	Green	2353.8	3.92	2.53	2.224	2.635	15.59	27.55	19.48	39.32
20	Green	2354.7	3.89	2.55	2.104	2.655	20.76	9.73	9.87	519.8
21	Dk Blue	2355.6	3.95	2.55	2.167	2.639	17.88	25.78	16.99	449.4
22	Green	2356.5	3.92	2.54	2.335	2.651	11.91	13.98	21.69	2.28
Well 32-8										
1A	Purple	2419.0	4.787	3.770	2.40	2.824	15.05	6.22	15.27	0.843
2A	Purple	2420.0	4.594	3.767	2.30	2.674	13.91	8.70	10.34	0.510
3A	Dk Blue	2420.8	4.325	3.766	2.28	2.652	14.07	12.24	12.20	2.276
4A	Green	2421.8	4.573	3.761	2.24	2.731	18.11	5.43	15.18	1.537
5A	Dk Blue	2422.6	4.500	3.765	2.27	2.652	14.38	7.63	7.97	1.076
6A	Dk Blue	2423.6	4.493	3.763	2.32	2.668	13.06	10.12	11.47	0.893
7A	Dk Blue	2424.5	4.435	3.763	2.31	2.668	13.26	4.74	17.14	1.551
8A	Dk Blue	2425.4	4.681	3.761	2.34	2.663	12.12	9.36	12.15	0.444
9A	Dk Blue	2426.2	4.706	3.762	2.30	2.660	13.69	10.26	11.55	0.700
10A	Dk Blue	2427.3	4.475	3.754	2.37	2.667	11.28	15.12	8.95	0.626
11A	Dk Blue	2428.2	4.739	3.767	2.29	2.725	16.13	8.21	15.50	0.921
12A	Dk Blue	2429.4	4.917	3.763	2.23	2.649	15.96	11.46	11.55	1.311
13A	Dk Blue	2429.9	4.447	3.762	2.32	2.644	12.22	13.25	8.59	0.626
14A	Dk Blue	2430.8	4.816	3.764	2.32	2.649	12.29	12.30	10.20	0.728
15A	Dk Blue	2431.7	4.517	3.759	2.32	2.648	12.34	10.66	13.59	1.499
16A	Dk Blue	2432.8	4.627	3.766	2.38	2.655	10.43	9.58	20.65	0.678
17A	Dk Blue	2433.6	4.550	3.764	2.29	2.646	13.61	12.48	11.71	2.763
18A	Green	2434.6	4.715	3.766	2.33	2.645	11.78	11.87	8.42	0.884
19A	Dk Blue	2435.5	4.556	3.764	2.36	2.653	10.99	10.77	9.23	0.569
20A	Dk Blue	2443.7	4.962	3.766	2.30	2.680	14.24	6.29	37.58	1.056
21A	Dk Blue	2444.5	4.781	3.764	2.25	2.646	14.83	6.21	44.03	0.790
22A	Dk Blue	2445.5	4.251	3.762	2.18	2.657	17.93	3.89	39.42	12.256
23A	Dk Blue	2446.4	4.921	3.770	2.198	2.649	17.02	3.32	44.81	23.415

** Results obtained from AP608 CoreTest Machine, 400 psi for Well 13-14 and 500 psi for Well 32-8

Table S5. Terra Tek Tight rock analysis for mudstone and limestone lithofacies in the upper Morrow shale and Thirteen Finger limestone.

ID	HRA Rock Class	Facies	Core Depth (ft)	Bulk Density (g/cc)	Dry Grain Density (g/cc)	Gas-Filled Porosity (% of BV)	HC-Filled Porosity (% of BV)	Porosity (% of BV)	Water Sat (% of PV)	Gas Sat (% of PV)	Oil Sat (% of PV)	Pressure-Decay Permeability (mD)
Well 13-10A												
64	Olive	bcm	2279.6	2.66	2.72	1.69	2.13	2.52	15.51	67.05	17.44	7.0e-5
70	Lt Blue	bcm	2293.9	2.69	2.73	1.19	1.20	1.21	0.82	98.37	0.82	6.0e-5
78	Purple	bcm	2299.1	2.46	2.56	2.32	3.05	6.64	54.04	34.88	11.08	1.1e-4
73	Black	bcm	2318.0	2.51	2.63	3.09	3.41	5.35	36.31	57.63	6.05	1.6e-4
79	Olive	coal	2320.1	1.40	*	8.18	*	*	*	*	*	2.0e-4
80	Brown	cm	2326.5	2.45	2.70	7.69	7.75	10.06	23.04	76.36	0.61	2.0e-4
81	Yellow	gbm	2332.9	2.54	2.66	2.47	2.56	5.83	56.10	42.46	1.44	1.2e-4
82	Yellow	gbm	2334.2	2.56	2.68	2.88	2.97	5.33	44.33	54.08	1.60	1.4e-4
E6	Purple	sl	2337.2	2.61	2.70	1.32	1.49	4.87	69.34	27.10	3.57	6.0e-5
69	Dk Blue	gbm	2348.8	3.15	3.27	2.77	2.83	4.22	33.05	65.57	1.38	5.0e-5
83	Red	gbm	2351.8	2.59	2.69	1.68	1.72	5.07	66.03	33.03	0.94	6.0e-5
Well 13-14												
53	Lt Blue	mmt	2034.5	2.65	2.72	2.57	2.75	2.94	6.64	87.38	5.98	4.0e-5
54	Black	mmt	2035.1	2.66	2.72	2.13	2.22	2.51	11.68	84.81	3.50	4.0e-5
55	Lt Blue	mmt	2046.4	2.62	2.70	2.35	2.44	3.41	28.37	69.08	2.55	9.0e-5
56	Grey	bcM	2321.1	2.40	2.51	2.05	2.56	5.84	56.20	35.14	8.66	7.0e-5
41	Orange	cC	2321.7	2.44	2.55	2.44	3.64	5.35	32.04	45.53	22.43	1.4e-4
42	Orange	blM	2329.3	2.44	2.64	1.94	2.02	11.39	82.22	17.07	0.71	6.0e-5
43	Orange	blM	2338.4	2.34	2.62	1.91	2.02	16.16	87.47	11.82	0.71	8.0e-5
44	Orange	blM	2340.9	2.56	2.75	1.34	1.43	7.57	81.09	17.77	1.14	5.0e-5
45	Orange	blM	2341.2	3.12	3.20	1.42	1.62	2.89	43.87	48.95	7.18	7.0e-5
46	Purple	blM	2341.8	2.42	2.59	3.11	3.19	8.52	62.50	36.50	1.00	6.0e-5
57	Yellow	gbM	2343.0	2.55	2.66	1.64	1.73	5.39	68.01	30.42	1.57	8.0e-5
47	Yellow	gbM	2346.4	2.55	2.65	1.72	1.81	5.10	64.49	33.85	1.66	6.0e-5
48	Purple	sL	2347.0	2.62	2.70	1.62	1.79	3.71	51.68	43.67	4.65	5.0e-5
51	Black	gbM	2357.0	2.53	2.66	3.00	3.08	6.17	50.03	48.61	1.36	6.0e-5
52	Yellow	gbM	2357.6	3.01	3.10	1.88	2.08	3.73	44.22	50.47	5.31	8.0e-5
Well 32-8												
25	Black	bcM	2382.6	2.68	2.69	0.17	0.19	0.20	4.91	85.28	9.81	4.4e-5
27	Orange	bcM	2391.2	2.27	2.37	1.59	2.26	5.53	59.10	28.77	12.12	8.5e-5
28	Lt Blue	Cs	2394.2	2.63	2.68	1.27	1.56	2.72	42.61	46.74	10.65	5.6e-5
29	Grey	Cs	2396.9	2.63	2.68	1.13	1.32	2.29	42.30	49.24	8.46	5.8e-5
31	Brown	gbM	2412.5	2.60	2.68	1.65	1.68	3.70	54.64	44.58	0.78	6.3e-5
32†	Purple	gbM	2418.3	2.57	2.66	2.03	2.06	4.06	49.23	50.07	0.70	1.9e-3* 2.5e-4**
52	Yellow	gbM	2440.8	2.58	2.65	1.34	1.36	3.74	63.55	35.94	0.51	4.0e-5
53†	Black	gbM	2443.0	2.57	2.65	3.03	3.13	3.41	8.34	88.88	2.78	1.4e-3* 1.8e-4** 6.7e-5***
57	Purple	blM	2449.4	2.57	2.61	0.92	0.96	2.47	61.27	37.19	1.53	4.6e-5

*** NSA for Retort - 'Coal' Sample plugged pressure vessel and zero fluids recovered. † Due to the high permeability of these samples, they were outside of the pressure decay perm testing range. They were instead tested with the pulse decay system: *performed at *500 psi, **1500 psi, ***3000 psi mD confining pressure.**

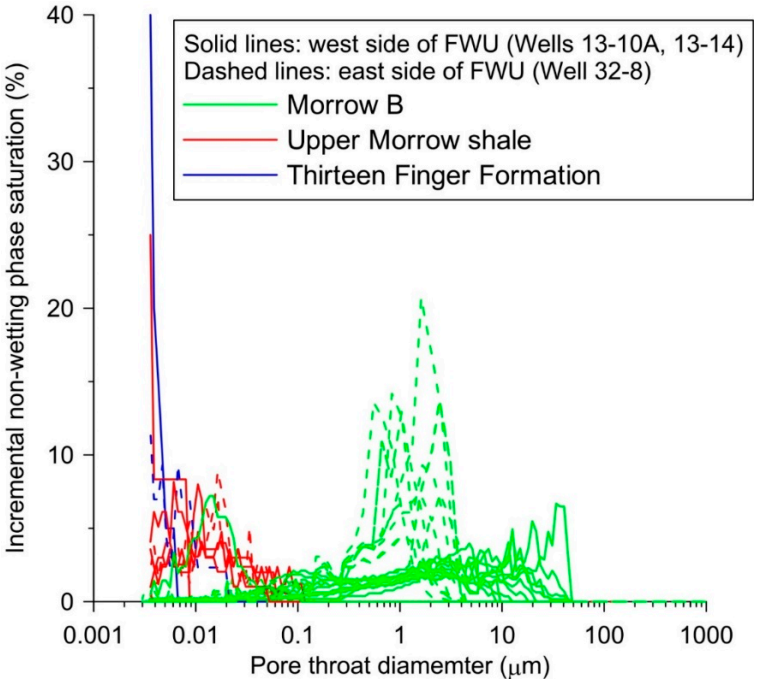

Figure S3. Pore throat diameter in microns vs. incremental non-wetting phase saturation, by formation and well location, determined from mercury porosimetry. Green lines show all data for Morrow B sandstone, red lines show all data for upper Morrow shale, and blue lines show data for Thirteen Finger limestone. The Morrow B sandstone has a range in pore throat diameters from 0.003 to 1000 μm. The pore throat diameter at the maximum breakthrough pressure is 44.3 μm. This corresponds to breakthrough pressures ranging from 0.03 to 0.77 MPa (4.8 to 112 psi) for the sandstone reservoir. The average pore throat diameter for the Morrow B sandstone is 14 μm with a median of 7 μm. The Morrow B sandstone has a bimodal distribution in pore throat diameters, with samples having either a peak in the 0.3–4 μm range or 10–80 μm range. This distribution relates to sandstones in different wells, with the 10- 80 μm range for sandstones from wells 13-10A and 13-14, and the 0.3-4 μm range for the sandstones from well 32-08. As discussed by [2], this bimodal distribution reflects abundant diagenetic microporosity in the Morrow B sandstone that exerts a first order dependence on multiphase flow properties of the sandstone flow units. The upper Morrow shale has much smaller pore throat diameters than the Morrow B sandstone ranging from 0.003 to 0.1 μm (Figure 7). The breakthrough pressure for the upper Morrow shale is much higher, ranging from 52.3 to 68.6 MPa (7589 to 9956 psi). The average pore throat diameter for the upper Morrow shale is 0.023 μm with a median of 0.026 μm. The pore apertures ranging from 0.003 to 0.1 μm have several peaks for the mudstones from all three wells, and there are notable differences between the east side of the FWU (well 32-8) and the west side of the FWU (wells 13-10A and 13-14) that may reflect diagenetic and/or depositional differences. The Thirteen Finger limestone, however, has breakthrough pressures ranging from 140.6 to 413.4 MPa (20399-59965 psi) with a range of pore throat diameters from 0.0047 to 0.0105 μm. The apparatus could not measure the breakthrough pressures for two of the cementstone samples because the pore throat diameters were too small and needed more pressure than the apparatus could sustain. The average pore throat diameter for the Thirteen Finger limestone is 0.0076 μm with a median of 0.0076 μm. The cementstone lithology within the Thirteen Finger limestone has the highest breakthrough pressures for the entire caprock at 413.4 MPa (59,965 psi) and has the smallest pore throat diameters. We do note however that difficulty in obtaining core plug samples for the mudstone lithofacies is somewhat biasing in MICP results for the caprock units.

Table S6. Mercury intrusion data and associated analysis by rock class for the 13-10A, 13-14, and 32-8 characterization wells.

Sample ID	HRA	Depth (m)	Plug orientation*	Cleaned	Formation	Break-through pressure, mercury-air (MPa)	CO2 column height, θ=10° (m)	CO2 column height, θ=57° (m)	Calc. Perm (mD)	Breakthrough pore-throat diameter (μm)
Well 13-10A										
70	Lt Blue	2294.2	v	Yes	13 Finger	413.45	11681.4	6460.3	0.00E+00	na
80	Brown	2326.8	v	Yes	Upper MS	62.59	1768.4	978.0	2.00E-05	0.0235
82	Yellow	2334.2	v	Yes	Upper MS	57.27	1618.0	894.8	2.34E-04	0.0257
E6	Brown	2337.2	h	Yes	Upper MS	52.34	1478.9	817.9	5.36E-05	0.0281
53	Dk Blue	2338.9	h	Yes	Morrow B	0.18	5.2	2.9	1.82E+00	8.0251
54	Dk Blue	2338.9	h	No	Morrow B	0.05	1.3	0.7	1.59E+01	31.0016
E1	Dk Blue	2339.6	h	Yes	Morrow B	0.14	4.0	2.2	9.12E+00	10.5157
E2	Dk Blue	2342.3	h	Yes	Morrow B	0.24	6.8	3.7	2.54E+00	6.1327
E3	Dk Blue	2342.8	h	Yes	Morrow B	0.14	4.0	2.2	3.67E+00	10.5156
55	Dk Blue	2343.2	h	Yes	Morrow B	0.05	1.5	0.8	6.48E+01	28.2851
56	Dk Blue	2343.2	h	No	Morrow B	0.04	1.2	0.7	1.48E+02	33.832
57	Dk Blue	2344.3	h	Yes	Morrow B	0.07	2.1	1.2	1.90E+01	19.7748
58	Dk Blue	2344.3	h	No	Morrow B	0.05	1.5	0.8	2.67E+01	28.3262
E4	Dk Blue	2345.8	h	Yes	Morrow B	0.07	2.1	1.2	3.25E+01	19.7912
59	Dk Blue	2347.3	h	Yes	Morrow B	0.03	0.9	0.5	1.22E+02	44.331
60	Red	2348.8	h	No	Morrow B	0.03	0.9	0.5	1.38E+02	44.3042
Well 13-14										
41	Black	2321.7	v	No	13 Finger	315.48	8955.1	4952.5	1.04E-06	0.0047
45	Yellow	2341.3	v	No	Upper MS	377.56	10717.2	5927.1	2.05E-06	0.0039
48	Purple	2347.1	v	No	Upper MS	68.64	1948.5	1077.6	5.05E-05	0.0214
49	Purple	2347.5	v	Yes	Morrow B	0.08	2.3	1.3	1.36E+01	18.0958
50	Purple	2347.5	v	Yes	Morrow B	0.26	7.5	4.1	1.49E+00	5.567
52	Red	2357.7	v	No	Lower MB	57.29	1626.2	899.3	6.78E-05	0.0257
Well 32-8										
25	Black	2382.9	v	No	13 Finger	140.65	4079.6	2256.2	3.90E-06	0.0105
31	Brown	2412.5	v	No	Upper MS	52.32	1517.6	839.3	1.30E-04	0.0281
32	Purple	2418.5	v	No	Upper MS	47.84	1387.5	767.4	5.24E-05	0.0307
34	Purple	2419.5	h	No	Morrow B	0.58	16.7	9.2	4.73E-01	2.5531
36	Dk Blue	2421.5	v	No	Morrow B	0.32	9.2	5.1	1.73E+00	3.9137
37	Dk Blue	2423.7	h	No	Morrow B	0.61	17.8	9.9	3.50E-01	2.0291
38	Green	2424.2	h	No	Morrow B	0.32	9.2	5.1	1.70E+00	3.9137
40	Dk Blue	2427.2	h	No	Morrow B	0.61	17.8	9.9	3.59E-01	2.0291
41	Dk Blue	2427.6	h	No	Morrow B	0.77	22.5	12.4	2.60E-01	1.6105
42	Dk Blue	2427.7	h	No	Morrow B	0.60	17.4	9.6	7.90E-01	2.0736
44	Green	2428.6	h	No	Morrow B	0.37	10.8	6.0	1.03E+00	3.3451
45	Dk Blue	2432.2	v	No	Morrow B	0.39	11.3	6.2	1.40E+00	3.2039
46	Dk Blue	2433.3	h	No	Morrow B	0.29	8.5	4.7	6.96E-01	4.2692
53	Black	2443.2	v	No	lower sand	1.72	49.8	27.6	6.94E-02	0.8561
54	Dk Blue	2445.2	h	No	lower sand	0.14	4.1	2.2	5.51E+00	10.488

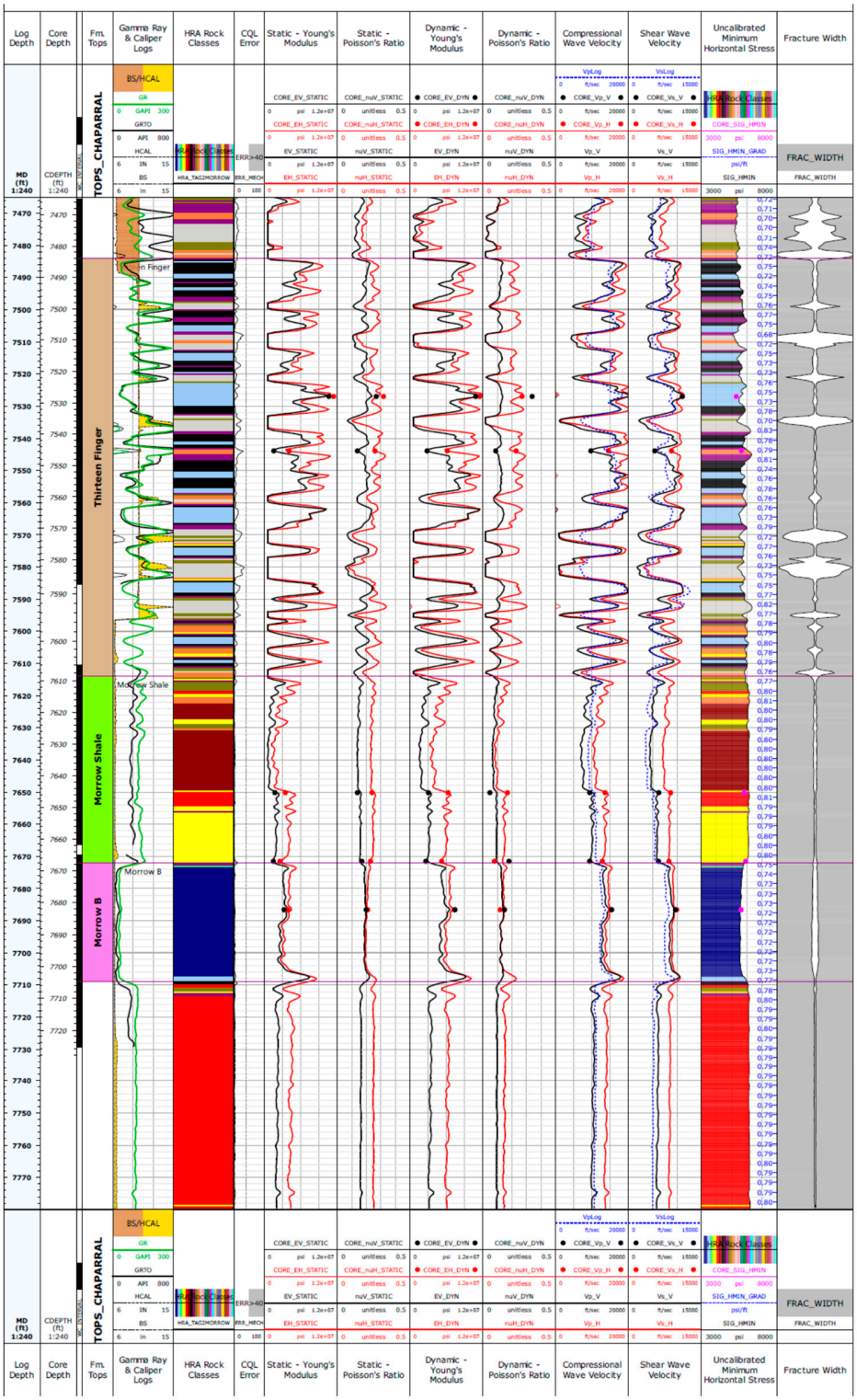

Figure S4. Well 13-10A interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots).

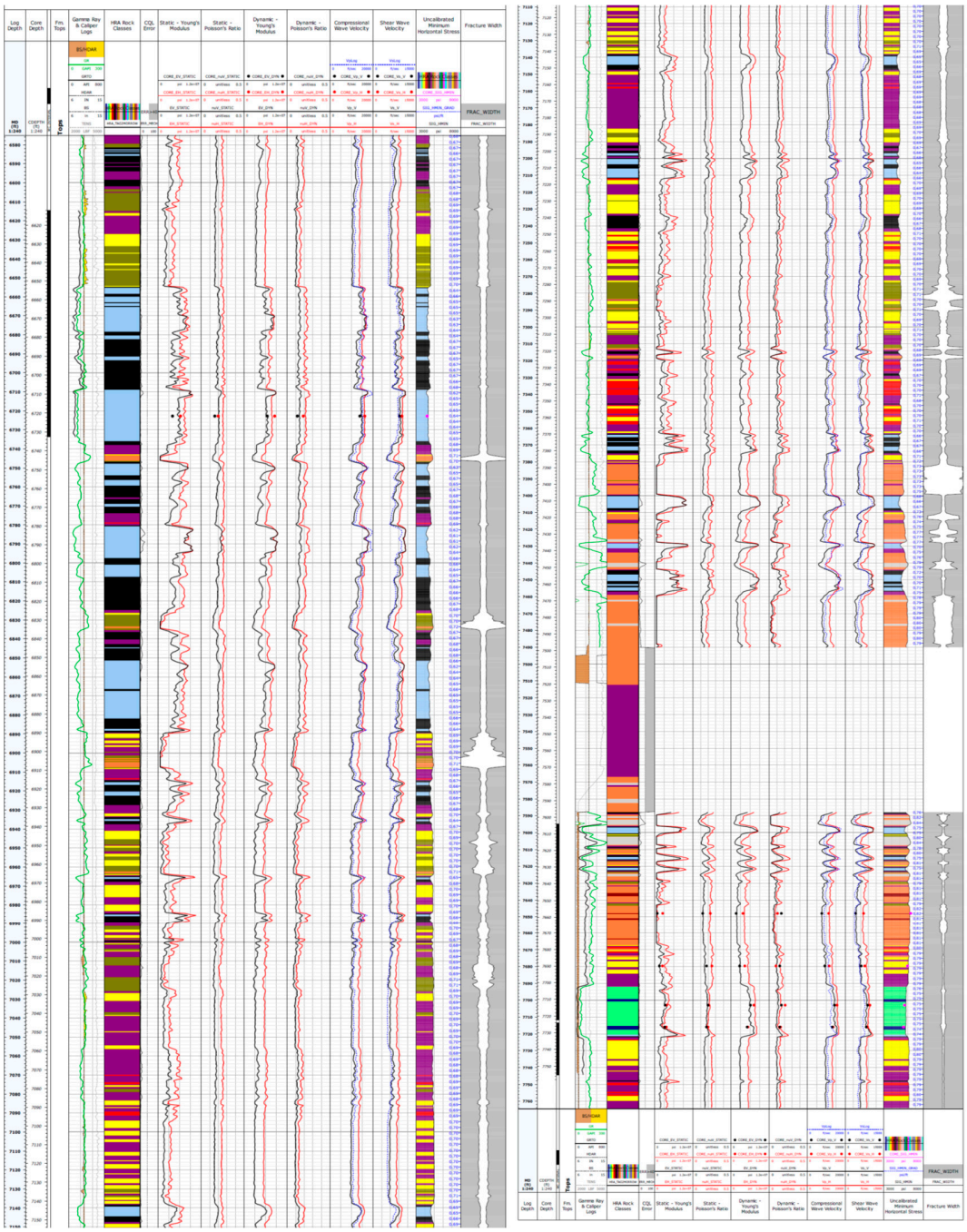

Figure S5. Well 13-14 interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots).

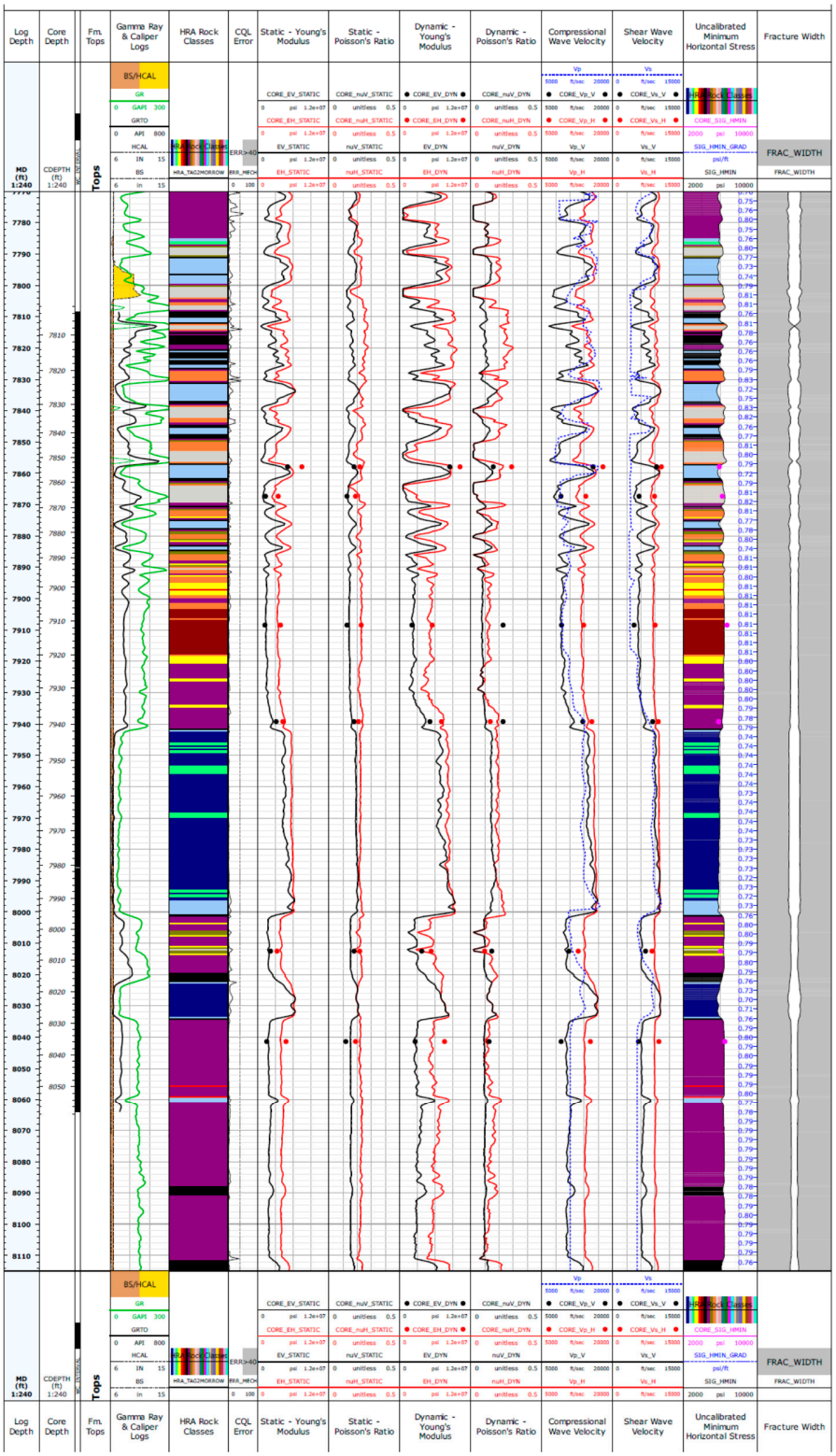

Figure S6. Well 32-8 interpolated static and dynamic rock mechanics properties based on Schlumberger/Terra Tek HRA log analysis and lab experiments (shown as red and black dots). Remarks made by Schlumberger:

1. Eleven rock classes are defined by the Morrow multi-well Heterogeneous Rock Analysis (HRA) model.
2. The mechanical properties presented in the Completion Quality Log (CQL) are modeled from the Farnsworth Unit 1310A and Farnsworth Unit 1314 core results. Predictions are displayed as continuous curves whereas core data are shown as circles. Error associated with the predictions is presented in the CQL Error track, where gray shading indicates intervals with high uncertainty. Caution should be taken when interpreting the results over these intervals.
3. The minimum horizontal stress and its gradient are presented in the Uncalibrated Minimum Horizontal Stress track where the HRA rock classes are profiled by the calculated stress. The following parameters were used for the stress calculation: pore pressure gradient varies from 0.43 to 0.59 psi/ft over the displayed interval based on sonic scanner mechanical properties logs; overburden stress gradient = 1.08 psi/ft. The far-field minimum horizontal stress calculation is based on a gravity loading model, accounting for the rock anisotropic mechanical behavior; no corrections were applied with respect to any tectonic lateral strain or basin subsidence/uplifting effects. 4. The fracture width, presented in the Fracture Width track, is a unitless prediction of the relative net pressure required to fracture the rock at a given depth, normalized over the interval displayed in the CQL. Wider widths are associated with lower breakdown pressures whereas narrower widths are associated with higher breakdown pressures.

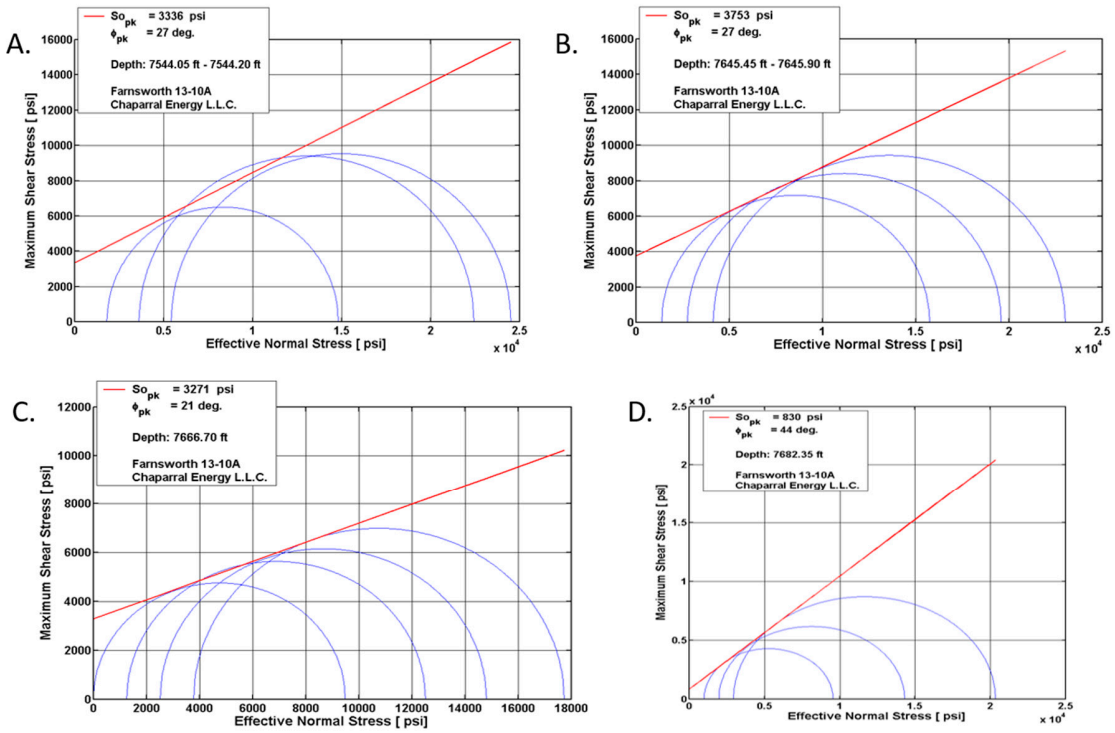

Figure S7. Example Coulomb failure envelopes for Well 13-10A. **(A.)** Coulomb failure envelope (i.e., shear dilatant failure) measured during triaxial compression testing of samples from HRA Unit Orange (7544.05 - 7544.20 ft, Thirteen Finger limestone). Linear failure parameters of cohesion and friction angle are provided for failure (peak values). **(B)** Same as A except for HRA Unit Red (7645.45 - 7645.90 ft , Morrow Shale). **(C)** Same as B and C except for HRA Unit Yellow (7666.70 ft, Morrow shale). **(D)** Same as A, B, and C except for HRA Unit Dark Blue (7682.35 ft, Morrow B sandstone). Figure 11A and B show the shear dilatant behavior of the weaker rock types tested, Blm mudstones from the Thirteen Finger Limestone (rock class Orange as shown in Figure 4) in Figure 11A, and from the upper Morrow shale (rock class Red, a laminated mudstone as shown in Figure 4). The two mudstones behave very similarly, with an angle of internal friction ϕ equal to 27°, and an apparent cohesion of around 3500 psi. A slightly weaker shale tested was a silty mudstone from the Morrow shale (Figure 11C, rock class Yellow) with a lower ϕ of 21° and an apparent cohesion of ~3200 psi.

Morrow B sandstones are apparently much weaker, as shown in Figure 11D. The sandstones have a greater ϕ of 44°, but a very low cohesive strength of 830 psi. This analysis shows that the sandstones of the Morrow B subjected to in situ stress conditions below the failure envelopes in Figure 11 would be more highly likely to experience shear failure associated with fluid injection than the mudstone formations. This is suggested as well by Brazil tensile failure tests for the Morrow B sandstone, Morrow shale, and Thirteen Finger limestone discussed by Trujillo ([10], her Figure 35), which show that the caprock lithologies in general have two to four times the tensile strength as compared to the Morrow B sandstones. Trujillo [10] also shows that a sample of cementstone from the Thirteen Finger limestone has apparently an incredibly high unconfined compressive strength of ~47 kpsi, which is approaching that of some crystalline rocks.

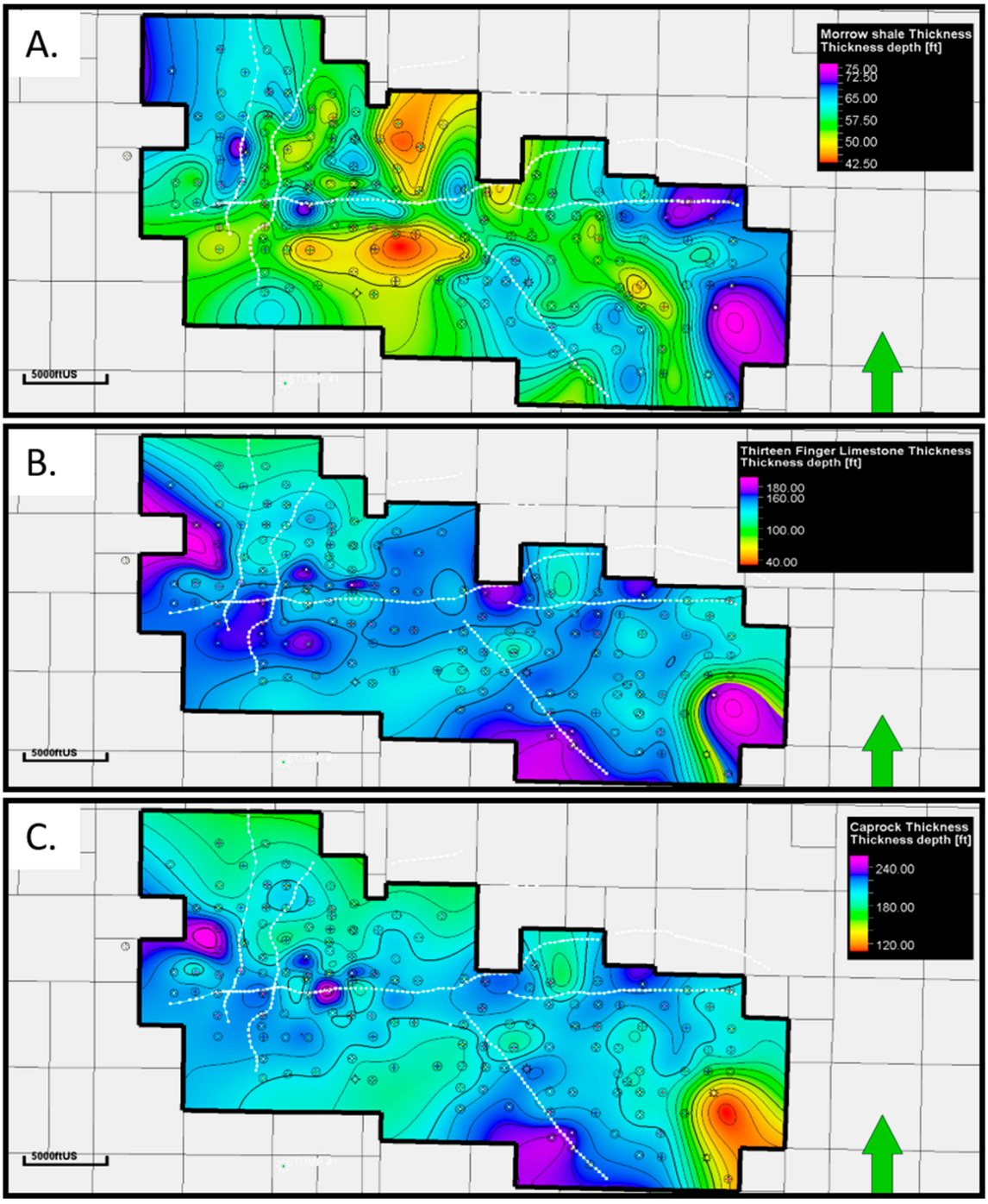

Figure S8. Isopach maps of caprock lithologies in the Farnsworth Unit. A. upper Morrow shale B. Thirteen Finger limestone. C. Total caprock thickness (after Rose-Coss, 2017; 100 ft equals 30.5 m).

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. "STP" stands for standard pressure and temperature.

Core depth (m)	Sample mass (g)	Wet bulk	Total porosity	^{3}He (cm^3 STP)	^{4}He (cm^3 STP)	^{20}Ne (cm^3 STP)	^{22}Ne (cm^3 STP)	^{36}Ar (cm^3 STP)	^{40}Ar (cm^3 STP)	R/R_a	$^{20}Ne/^{22}Ne$	$^{36}Ar/^{40}Ar$	$^{4}He/^{20}Ne$
2275.4	267.57	2.43	0.07	2.74E-11	1.22E-03	2.03E-08	1.39E-09	-	-	0.016	1.46E+01	-	6.04E+04
2276.0	135.8	2.69	0.01	3.81E-12	1.43E-04	2.16E-07	1.99E-08	-	1.69E-04	0.019	1.08E+01	-	6.63E+02
2277.5	187.566	2.43	0.07	2.26E-12	8.62E-05	1.25E-08	1.06E-09	-	-	0.019	1.18E+01	-	6.89E+03
2280.2	191.256	2.43	0.07	4.52E-11	1.67E-03	3.67E-08	2.60E-09	1.56E-06	1.45E-04	0.020	1.41E+01	1.08E-02	4.54E+04
2286.5	225.226	2.43	0.07	4.08E-12	1.63E-04	5.18E-08	4.66E-09	1.89E-06	2.23E-04	0.034	1.11E+01	8.48E-03	3.15E+03
2290.6	216.491	2.63	0.06	4.64E-11	2.15E-04	1.11E-04	1.11E-05	2.05E-04	6.06E-02	0.470	1.00E+01	3.38E-03	1.93E+00
2292.7	185.263	2.20	0.33	1.23E-12	5.66E-05	9.18E-09	5.28E-10	-	1.03E-04	0.016	1.74E+01	-	6.16E+03
2318.0	240.4	2.51	0.05	5.28E-11	1.95E-03	2.56E-08	1.86E-09	-	2.17E-04	0.020	1.38E+01	-	7.65E+04
2321.9	209.52	2.51	0.05	3.48E-11	1.26E-03	4.19E-08	2.36E-09	-	4.71E-04	0.020	1.78E+01	-	3.02E+04
2325.2	154.82	2.51	0.05	4.96E-11	1.96E-03	9.53E-08	8.93E-09	-	5.82E-05	0.018	1.07E+01	-	2.05E+04
2329.4	150.96	2.51	0.05	3.93E-11	1.45E-03	3.26E-08	1.75E-09	-	-	0.020	1.87E+01	-	4.46E+04
2332.1	187.22	2.54	0.06	4.41E-11	1.79E-03	9.27E-08	6.75E-09	9.40E-09	1.86E-04	0.018	1.37E+01	5.06E-05	1.93E+04
2335.3	159.72	2.56	0.05	7.53E-12	2.90E-04	2.42E-08	1.65E-09	1.84E-06	2.51E-04	0.019	1.47E+01	7.32E-03	1.20E+04
2337.8	145.36	2.41	0.15	2.87E-13	9.30E-06	4.09E-08	3.69E-09	-	-	0.022	1.11E+01	-	2.27E+02
2340.6	233.62	2.41	0.14	6.42E-11	5.06E-05	1.36E-04	1.31E-05	2.49E-04	7.08E-02	2.763	1.04E+01	3.52E-03	3.73E-01
2343.3	209.37	2.33	0.19	3.72E-14	2.11E-06	1.54E-08	1.12E-10	-	2.87E-04	0.013	1.37E+02	-	1.37E+02
2345.2	99.57	2.34	0.18	3.85E-13	1.65E-05	1.73E-07	1.43E-08	1.51E-06	1.89E-04	0.299	1.21E+01	8.02E-03	9.52E+01
2347.0	136.22	2.35	0.18	1.15E-12	3.88E-05	2.70E-07	2.26E-08	5.67E-06	4.31E-04	0.111	1.20E+01	1.31E-02	1.44E+02
2354.2	685.73	2.64	0.13	5.62E-11	2.11E-03	7.08E-08	4.70E-09	-	2.39E-04	0.019	1.51E+01	-	2.99E+04