RENEWED EXPLORATION IN THE RED RIVER FORMATION IN SOUTHWESTERN NORTH DAKOTA USING 3-D SEISMIC

by

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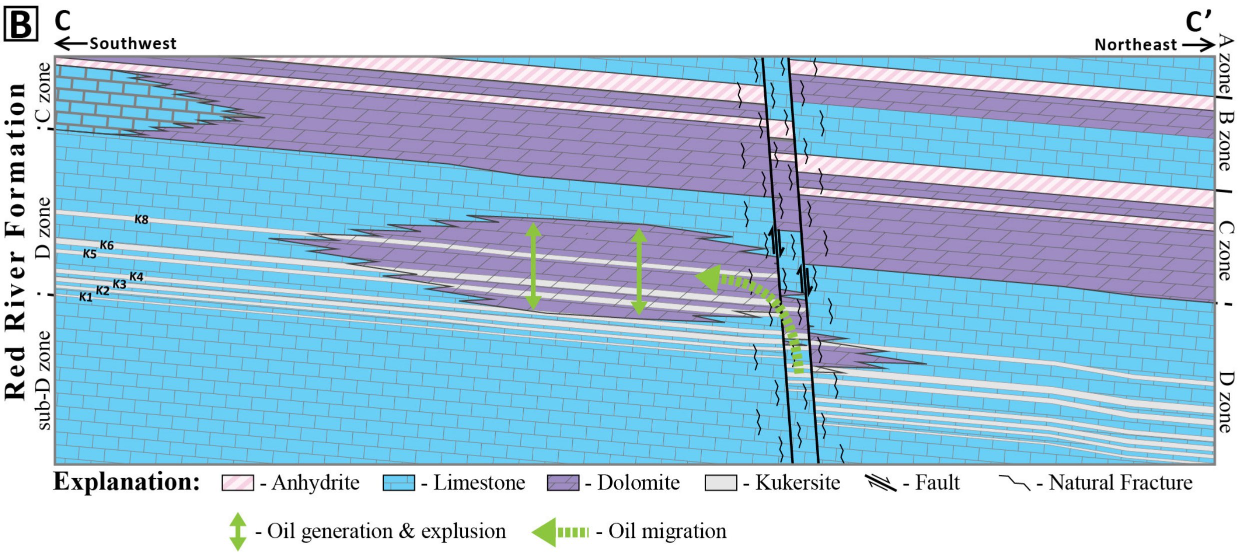

REPORT OF INVESTIGATION NO. 138
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
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Schematic cross-sections depicting hypothesized relationship between faulting and hydrocarbon charge in the Red River D interval.

INTRODUCTION

Over 1,400 vertical and horizontal Red River wells have produced more than 330 million barrels of oil within North Dakota, and >2,800 Red River wells across the entire Williston Basin have produced more than 560 million barrels of oil (Fig. 1). Substantial vertical well exploration and development of Red River reservoirs was concentrated along the Cedar Creek anticline and northeastern Montana during and prior to the 1980's (Kohm and Louden, 1978; Longman et al., 1983). Horizontal drilling in the Red River "B" interval in southwestern North Dakota from 1995-1996 led to the development of the Cedar Hills Field (Montgomery, 1997). The Red River Pool discovery in the Midale Field of southeastern Saskatchewan led to multiple Red River field discoveries in the northern portions of the Williston Basin (Kreis and Kent, 2000; Pu et al., 2003). Overall, the Red River Formation is the third most hydrocarbon productive interval in both North Dakota and across the entire Williston Basin behind the prolific Bakken-Three Forks Formations and the Mississippian Madison Group.

A 3-D seismic exploration and development program in Golden Valley County from 2010-2017 resulted in 32 Red River vertical/directional wells of which 24 have commercially produced oil and gas (~80% success rate). To date, those 24 wells have combined to yield 2.5 million barrels of oil. The area had previously been explored and developed using 2-D seismic which yielded only seven productive wells and 19 dry holes. Based upon records from public oil and gas hearings, 3-D seismic can be processed to identify high porosity versus low porosity zones within the Red River D interval, the primary Red River hydrocarbon reservoir in the area of interest (Hill et al., 2018).

The purpose of this report is to examine publicly available wireline logs, cores, and

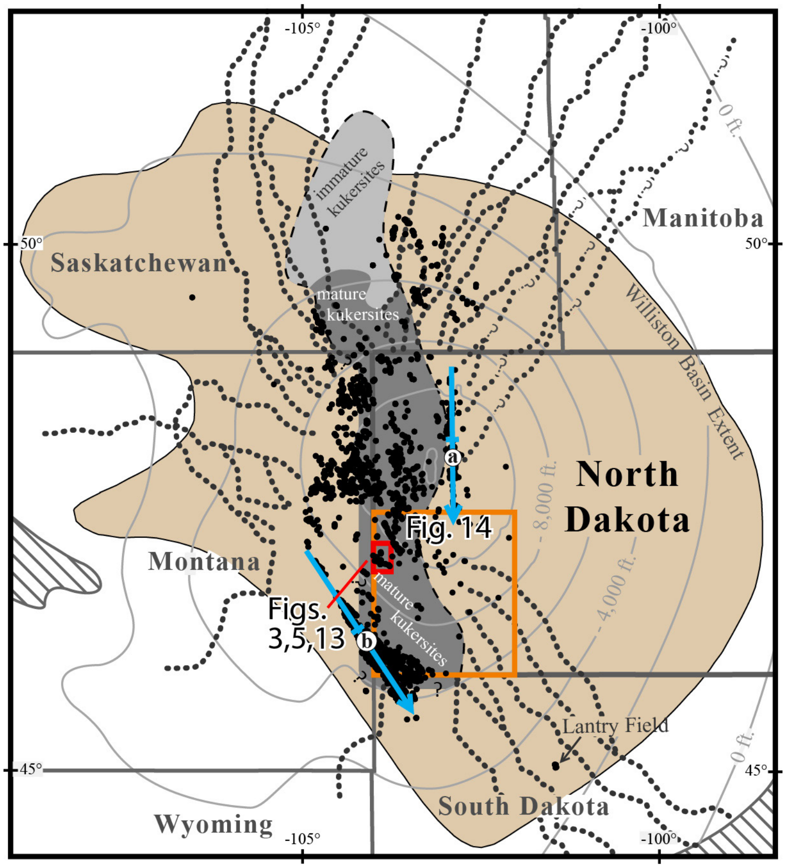


FIGURE 1. Hydrocarbon generation and migration map for the Red River Petroleum System within the Williston Basin. Black dots depict Red River productive oil and gas wells. Red River kukersite extent (light and dark grey) compiled from Nesheim (2017a, b), Osadetz and Haidl (1989), and Osadetz and Snowdon (1995). The dotted black lines are modeled hydrocarbon migration pathways within the Red River Formation modified from Khan et al. (2006). The faint gray lines depict structure contours on the Red River Formation top. a = Nesson anticline; b = Cedar Creek anticline.

production records along with the limited 3-D seismic maps from oil and gas hearings to determine the feasibility of using 3-D seismic for Red River D interval exploration. Additionally, this report will evaluate the variable well results which range from ~3 to 300+ thousand barrels of oil (MBO) cumulative production to determine geologic controls on well performance in addition to reservoir quality/ presence.

GEOLOGIC BACKGROUND

The Red River Formation is a Late Ordovician carbonate-evaporite super sequence in which the upper Red River (approximately equivalent to the Herald Formation of Saskatchewan) is comprised of three transgressive-regressive sequences (Husinec, 2016) (Fig. 2). Subaqueous anhydrites represent evaporite lowstand systems tracts of each upper Red River sequence, skeletal mudstone to wackestone-packstone with abundant burrow mottling comprise the subtidal deposits of the transgressive and early highstand systems tracts (HSTs), and peritidal, porous laminated dolostone compose the Late HSTs (Husinec, 2016). Laminated dolostones form hydrocarbon reservoirs capped by basin-centered anhydrite beds (which form hydrocarbon seals) within the A, B, and C intervals of the upper Red River (Longman et al., 1983) (Fig. 2).

The lower Red River (approximately equivalent to the Yeoman Formation of Saskatchewan) comprises approximately two-thirds of the unit and predominantly consists of dolomitic, burrow-mottled, lime mudstone to fossil wackestone in the central basin with normal marine fossil assemblages (Kohm and Louden, 1978) (Fig. 2). *Thalassinoides*

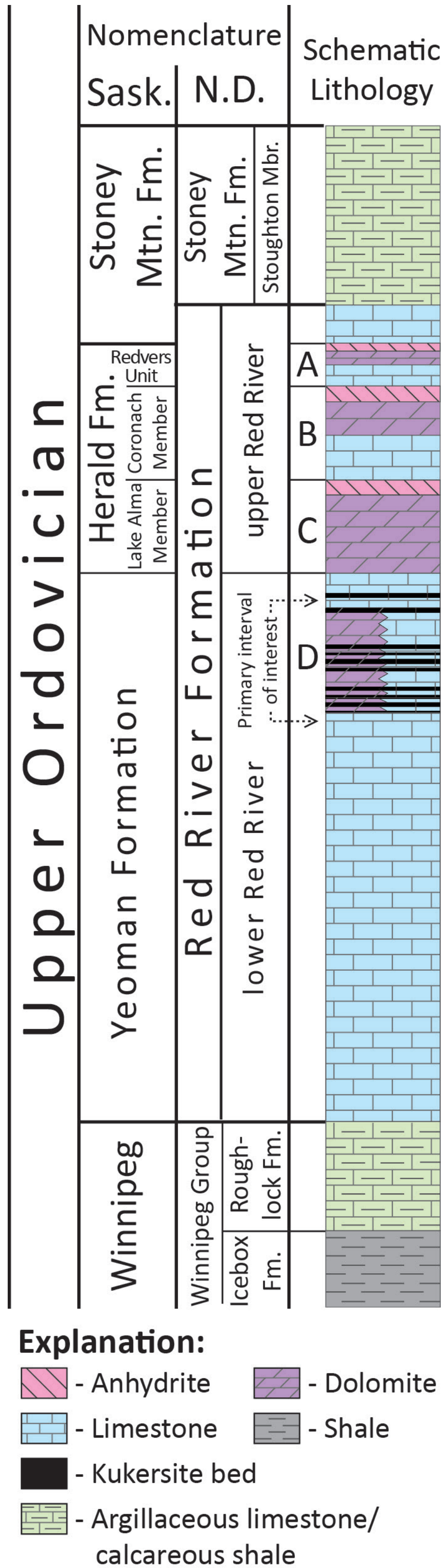


FIGURE 2. Stratigraphic column of the Upper Ordovician Red River Formation (Fm.), Williston Basin comparing nomenclature from Murphy et al. (2009) for North Dakota (N.D.) and Kendall (1976) for Saskatchewan (Sask.). Mbr. = member; Mtn. = mountain.

burrows, typically several centimeters in diameter, are thought to be a primary contributor to the lower Red River's mottled texture (Pak and Pemberton, 2003; Pak et al., 2010). The upper 150 ft (46 m) of the lower Red River has been partially to completely dolomitized and is informally referred to as the D zone, D porosity and/or D interval (Derby and Kilpatrick, 1985; Montgomery, 1997; Nesheim, 2017a). Laminated dolostone of the B interval and dolomitized burrow-mottled facies of the D interval comprise the two primary reservoir facies of the unit. Secondarily, laminated dolostone in the A and C intervals are also productive. A series of thin, organic-rich carbonate mudstone beds, with abundant amounts of the algal microfossil *Gloeocapsomorpha prisca*, occur interbedded with the burrow-mottled wacke-mudstone in the D interval, which are believed to be the primary source of Red River hydrocarbons (Stasiuk and Osadetz, 1990; Nesheim, 2017a).

2-D SEISMIC RED RIVER EXPLORATION & DEVELOPMENT (1969-2000)

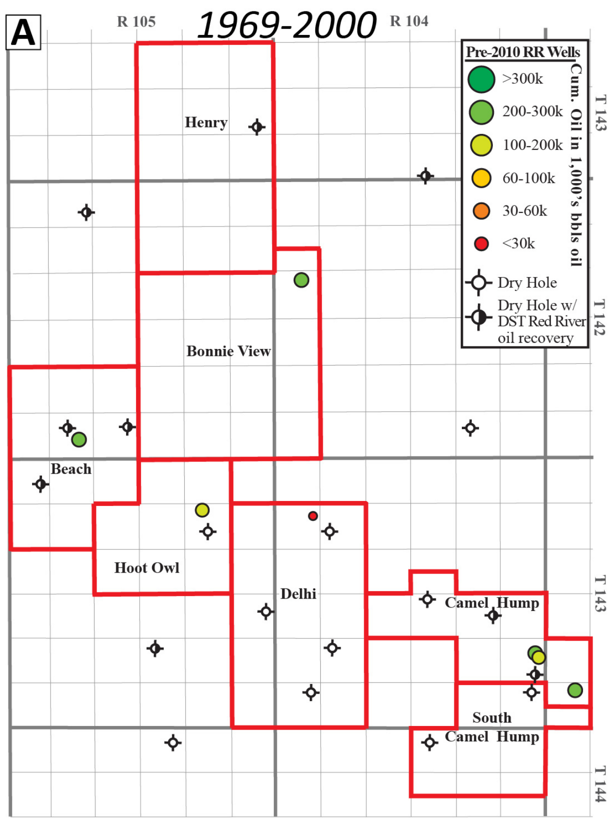
Between 1969 and 2000, 26 vertical and directional wells were drilled in the study area that penetrated the Red River Formation (Fig. 3a). Each of these wells were presumably drilled using 2-D seismic targeting interpreted structural highs (2-D seismic lines and other records are present in multiple oil and gas hearing files). There were a total of 19 dry holes and seven total commercial producers. Of the 19 dry holes, nine wells yielded non-commercial oil recoveries from drill stem tests (Fig. 3a). One of the commercially productive Red River wells only yielded 8.6 MBO before being plugged and abandoned while the other six wells cumulatively produced 108 MBO to 273 MBO per well (Table 1).

Two of the legacy Red River wells essentially represent the same well location. The Tescher #2 (NDIC: 7679, API: 33-033-00078-00-00) was spudded and completed in the Red River Formation in 1980 and produced 151 MBO before being prematurely plugged and abandoned due to a casing collapse in 1984. The Tescher #42-25 (NDIC: 12132, API: 33-033-00180) was drilled in 1987 proximal to the Tescher #2 (~250 feet apart) and produced another 215 MBO before being plugged and abandoned. The Tescher #2 and Tescher #42-25 wells essentially represent one well location that compositely yielded 366 MBO from the Red River Formation.

Overall, considering that one productive well only yielded 8.6 MBO and two other wells were the same location, only five Red River well locations yielded production of ≥100 MBO. This translated to approximately a ~20% success rate of production ≥100 MBO when utilizing 2-D seismic for Red River exploration within the study area. Total cumulative production from the seven productive Red River wells drilled using 2-D seismic is ~1.2 million barrels of oil (MMBO).

3-D SEISMIC RED RIVER EXPLORATION & DEVELOPMENT (2010-2017)

Between 2010 and 2017, 31 vertical/directional wells were drilled in the study area that penetrated the Red River Formation (4 additional horizontal Red River test wells were drilled and completed that are not reviewed herein) (Fig. 3b; Table 2). Most of these wells



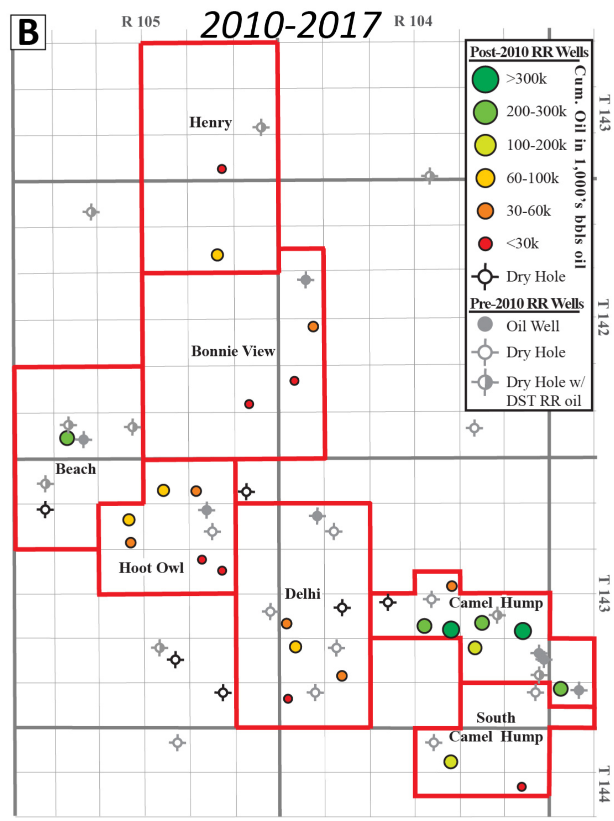


FIGURE 3. Field maps of the study area with Red River vertical/directional wells by time period: **A)** wells drilled during 1969-2000 (2-D seismic), **B)** wells drilled during 2010-17 (3-D seismic), and **C)** all Red River wells drilled in the study area. Current oil field boundaries are represented by red outlines.

TABLE 1. Information for vertical and directional wells that penetrated the Red River Formation in the study area during 1969-2000.

WELL INFORMATION						LOCATION INFORMATION					CUMULATIVE PRODUCITON DATA		
NDIC #	API Number	Well Name	Current Operator	Original Operator	TD (ft)	Latitude	Longitude	Section	Township	Range	Oil (BBLS)	Gas (MCF)	Water (BBLS)
4791	33033000300000	Slocomb #1	Woods Petroleum Corp.	Woods Petroleum Corp.	12,184	47.169235	-103.928072	29	141N	104W	Dry hole		
5438	33033000370000	Guy M. Brown etal #1	Texas Gas Exploration Corp.	Texas Gas Exploration Corp.	11,892	47.006494	-103.975792	27	141N	105W	Dry hole		
6513	33033000500000	Davidson #41-31	Shell Oil Company	Shell Oil Company	12,570	46.992407	-103.901904	31	141N	104W	Dry hole		
6920	33033000600000	Tescher #1	Jake L. Hamon	Jake L. Hamon & Samson Res. Co.	12,251	46.995674	-103.796914	25	141N	104W	Dry hole		
7679	33033000780000	Tescher #2	Hamon Operating Co.	Jake L. Hamon & Samson Res. Co.	12,210	47.001602	-103.795774	25	141N	104W	151,067	75,454	1,828
7753	33033000800000	Kunick #1	Kaneb Production Co.	Moran Exploration, Inc.	12,587	47.046695	-103.901866	7	141N	104W	8,621	400	60,333
7969	33033000850000	Stecker #1	Tipperary Oil & Gas Corp.	Moran Exploration, Inc.	12,325	47.072061	-104.012207	32	142N	105W	197,440	9,584	202,022
8127	33033000920000	Carlson #1	Moran Exploration, Inc.	Moran Exploration, Inc.	12,175	47.04126	-103.893913	8	141N	104W	Dry hole		
8233	33033000960000	Ueckert #1-11	Key Energy Services, LLC	Terra Res. & Moran Expl. Co.	12,240	47.050302	-103.954516	11	141N	105W	107,896	41,473	81,544
8324	33033000970000	7-142-104 BN #1	White Rock Oil & Gas, LLC	Gulf Oil Corp.	12,440	47.1227	-103.906905	18	142N	104W	273,491	207,210	124,337
8460	33033001000000	Tescher #3	Berco Resources, Inc.	Jake L. Hamon & Samson Res. Co.	12,250	46.990934	-103.779072	31	141N	103W	251,248	141,645	41,978
8713	33033001050000	Waldahl #1	Samson Resources Co.	Jake L. Hamon	12,399	46.974917	-103.847819	6	140N	104W	Dry hole		
8746	33033001060000	Wirtzfeld #1-23	Dome Petroleum Corp.	Dome Petroleum Corp.	12,361	47.016572	-103.817558	23	141N	104W	Dry hole		
8814	33033001070000	Kautzman #1	Pioneer Prod. Corp.	Pioneer Prod. Corp.	12,320	47.021436	-103.84924	22	141N	104W	Dry hole		
8943	33033001100000	Feldman #1	Moran Exploration, Inc.	Moran Exploration, Inc.	11,904	47.075786	-104.017947	32	142N	105W	Dry hole		
8959	33033001110000	Jones Ranch, Alaq, Stedr	Canterra Petroleum, Inc.	Al-Aquitaine Exploration, LTD.	12,550	47.154946	-103.847928	34	143N	104W	Marginal producer from Duperow Fm.		
8987	33033001130000	Kittelson #2-11	Terra Resources, Inc.	Terra Resources, Inc.	12,130	47.043089	-103.951895	11	141N	105W	Dry hole		
9011	33033001140000	Kukowski #1	Moran Exploration, Inc.	Moran Exploration, Inc.	11,860	46.975741	-103.968555	6	140N	105W	Dry hole		
9115	33033001180000	Trester #1	Moran Exploration, Inc.	Moran Exploration, Inc.	12,144	47.144096	-104.007618	5	142N	105W	Dry hole		
9165	33033001210000	Tescher #1-36	Samson Resources Co.	Samson Resources Co.	12,199	46.990732	-103.799017	36	141N	104W	Dry hole		
9172	33033001230000	Peterson #1	Moran Exploration, Inc.	Moran Exploration, Inc.	12,210	47.075891	-103.986704	33	142N	105W	Dry hole		
9211	33033001240000	Kunick #35-22	BWAB, Inc.	BWAB, Inc.	12,332	47.076003	-103.827386	35	142N	104W	Dry hole		
9350	33033001260000	A. Schaal #1	Moran Exploration, Inc.	Moran Exploration, Inc.	12,150	47.017658	-103.922761	24	141N	105W	Dry hole		
12132	33033001800000	Tescher #42-25	Whiting Oil & Gas Corp.	Meridian Oil, Inc.	12,260	47.00215	-103.796415	25	141N	104W	215,033	123,371	57,102
12714	33033001990000	Hathaway #1-6	Samedan Oil Corp.	Samedan Oil Corp.	11,950	47.057559	-104.028431	6	141N	105W	Dry hole		
14957	33033002250000	JN Peterson #34-25X	True Oil LLC	True Oil Co.	12,285	47.169257	-103.928594	25	143N	105W	Dry hole		

TABLE 2. Information for vertical and directional wells that penetrated the Red River Formation in the study area during 2010-2017.

WELL INFORMATION					LOCATION INFORMATION					CUMULATIVE PRODUCITON DATA		
NDIC #	**API Number**	**Well Name**	**Current Operator**	**Original Operator**	**Latitude**	**Longitude**	**Section**	**Township**	**Range**	**Oil (BBLS)**	**Gas (MCF)**	**Water (BBLS)**
23598	33033003170000	KITTELSON 32-27R	WHITING OIL AND GAS	WHITING OIL AND GAS	47.003566	-103.969759	27	141N	105W	Dry hole		
25240	33033003290000	K G RANCH 22-20	WHITING OIL AND GAS	WHITING OIL AND GAS	47.019308	-103.890279	20	141N	104W	Dry hole		
25395	33033003310000	KG RANCH 21-21	WHITING OIL AND GAS	WHITING OIL AND GAS	47.021085	-103.868926	21	141N	104W	Dry hole		
26056	33033003390000	SCHAAL 41-7	WHITING OIL AND GAS	WHITING OIL AND GAS	47.050291	-104.027862	7	141N	105W	Dry hole		
26351	33033003420000	LECHLER 42-35	WHITING OIL AND GAS	WHITING OIL AND GAS	46.990505	-103.945392	35	141N	105W	Dry hole		
38301	33033003670000	Fugere 31-23	ARMSTRONG OPERATING	ARMSTRONG OPERATING	46.984148	-103.783861	31	141N	103W	Dry hole		
24670	33033003240000	PLIENIS 24-24	FOUNDATION ENERGY	WHITING OIL AND GAS	47.009348	-103.806114	24	141N	104W	383,934	147,563	66,222
22750	33033003110000	RIECKOFF 44-22	FOUNDATION ENERGY	WHITING OIL AND GAS	47.011412	-103.838409	22	141N	104W	348,356	199,180	49,620
23330	33033003150000	SAMUELSON 23-32	FOUNDATION ENERGY	WHITING OIL AND GAS	47.072418	-104.017796	32	142N	105W	258,574	46,564	587,385
23533	33033003160000	KATHERINE 33-23	FOUNDATION ENERGY	WHITING OIL AND GAS	47.012876	-103.823781	23	141N	104W	235,776	164,324	96,897
19917	33033002980000	MAUS 23-22	FOUNDATION ENERGY	WHITING OIL AND GAS	47.013434	-103.850932	22	141N	104W	221,478	72,202	107,688
33741	33033003650000	FUGERE 3-31	FOUNDATION ENERGY	FOUNDATION ENERGY	46.991928	-103.787979	31	141N	103W	212,536	65,348	35,317
29562	33033003510000	LARDY 44-6	FOUNDATION ENERGY	WHITING OIL AND GAS	46.965079	-103.84365	6	140N	104W	121,385	24,533	77,080
26582	33033003450000	MAUS 21-26	FOUNDATION ENERGY	WHITING OIL AND GAS	47.005849	-103.827483	26	141N	104W	117,402	75,905	30,001
22374	33033003090000	QUALE 21-30	FOUNDATION ENERGY	WHITING OIL AND GAS	47.006852	-103.911817	30	141N	104W	87,122	20,477	169,465
22569	33033003100000	SAMUELSON 23-3	FOUNDATION ENERGY	WHITING OIL AND GAS	47.058035	-103.97533	3	141N	105W	79,965	11,846	131,236
26008	33033003380000	MCDANOLD 33-11	FOUNDATION ENERGY	WHITING OIL AND GAS	47.128544	-103.946467	11	142N	105W	67,354	16,096	60,845
23847	33033003180000	STECKER 32-9	FOUNDATION ENERGY	WHITING OIL AND GAS	47.046728	-103.990855	9	141N	105W	60,265	18,109	140,066
22775	33033003120000	ROSS 13-2	FOUNDATION ENERGY	WHITING OIL AND GAS	47.0581	-103.959308	2	141N	105W	56,165	22,642	143,783
24618	33033003230000	DAVIDSON 13-19	FOUNDATION ENERGY	WHITING OIL AND GAS	47.014859	-103.917468	19	141N	104W	55,164	18,866	120,541
20043	33033003000000	PEPLINSKI 34-9	FOUNDATION ENERGY	WHITING OIL AND GAS	47.039612	-103.990254	9	141N	105W	51,548	13,572	117,348
26425	33033003430000	LOWMAN 44-15	FOUNDATION ENERGY	WHITING OIL AND GAS	47.025419	-103.840469	15	141N	104W	46,791	27,827	40,836
25078	33033003260000	DAVIDSON 24-29	FOUNDATION ENERGY	WHITING OIL AND GAS	46.996614	-103.891961	29	141N	104W	32,467	3,767	215,436
24910	33033003250000	MEYERS 31-19	FOUNDATION ENERGY	WHITING OIL AND GAS	47.108595	-103.905098	19	142N	104W	30,478	3,746	149,987
25466	33033003320000	WILLIAMS 24-25	FOUNDATION ENERGY	WHITING OIL AND GAS	47.08295	-103.934135	25	142N	105W	25,223	5,744	139,120
23851	33033003190000	DAVIDSON 12-31	FOUNDATION ENERGY	WHITING OIL AND GAS	46.990064	-103.916073	31	141N	104W	19,396	4,739	160,031
18005	33033002940000	JONES 44-35	FOUNDATION ENERGY	WHITING OIL AND GAS	47.15532	-103.943652	35	143N	105W	14,728	1,445	208,851
19921	33033002990000	BROOKHART 11-14	FOUNDATION ENERGY	WHITING OIL AND GAS	47.034242	-103.957838	14	141N	105W	11,582	10,699	53,599
29720	33033003520000	ROJIC 22-9	FOUNDATION ENERGY	WHITING OIL AND GAS	46.958038	-103.812832	9	140N	104W	3,650	152	28,917
25984	33033003370000	STEDMAN 22-30	FOUNDATION ENERGY	WHITING OIL AND GAS	47.09011	-103.911533	30	142N	104W	3,213	7,843	92,159
23936	33033003210000	FAIMAN 32-14	FOUNDATION ENERGY	WHITING OIL AND GAS	47.031006	-103.947378	14	141N	105W	10	36	7,035
25338	33033003300000	JANDT 14-1-2	WHITING OIL AND GAS	WHITING OIL AND GAS	47.053883	-103.938137	1	141N	105W	0	37	5,035
									TOTALS	**2,544,562**	**983,262**	**3,034,500**

were drilled utilizing 3-D seismic to target high porosity development within the Red River D interval. Only seven of the 3-D seismic vertical wells were dry holes with no reported commercial oil production (well #23936 yield 10 barrels of oil but is considered a dry hole). The other 24 wells have cumulatively produced between 3.2 MBO and 384 MBO to date, from which total production is currently over 2.5 MMBO and multiple wells are still actively producing. The success rate for drilling Red River wells using 3-D seismic is ~77% for attaining at least a few thousand barrels of cumulative oil production.

As previously stated, production from the Red River wells drilled using 3-D seismic has been highly variable. Two of the recent Red River wells produced less than 4 MBO before being plugged and abandoned (~6%) while another seven wells have produced only between 10 MBO and 50 MBO (~23%). Seven wells have produced between 50 MBO and 100 MBO (~23%) and eight have produced between 100 MBO and 400 MBO (~26%). Seven out of the eight most productive wells (cumulative oil production >100 MBO) are located within the Camel Hump/South Camel Hump Fields in the southeastern portions of the study area (Fig. 3c).

METHODS

Monthly oil, gas, and water production data were compiled from NDIC records. Net perforation intervals were compiled from well files and combined with stratigraphic wireline log correlations. Structure contours of the Red River Formation top derived from 3-D seismic and interpreted porosity maps of the Red River D interval were compiled from exhibits submitted to public oil and gas hearings. Two Red River cores were logged at the Wilson M. Laird Core and Sample Library; Whiting Oil and Gas Corporation's Peplinski 34-9 (NDIC: 20043, API: 33-033-00300) and Schaal 22-15H (NDIC: 22956, API: 33-033-00313). Core to log depth adjustments were completed through a combination of core porosity to log porosity comparison and observed lithology to wireline logs (#20043: core – 3.3 ft. = log, #22956: core – 6.5 ft. = log). API oil gravity values were compiled from well files and early gas to oil ratios (GOR) were calculated from reported production data.

Preliminary petrophysical analysis was also conducted within the Red River D interval on select wells. The logs analyzed include resistivity (Rt), neutron (NPHI), and density (RHOB) logs to obtain porosity, water saturation (Sw), and bulk volume water (BVW). The porosity calculation used averaged porosity (PHIA) log derived from density porosity (DPHI) and neutron porosity (NPHI) logs, both on a limestone matrix. Sw was calculated using Archie's method (Archie, 1952) with constants (a, m, n) selected based on regional geology knowledge and refined using a modified Pickett Plot (Pickett, 1973). Formation water resistivity (Rw) was obtained from compiled laboratory water analyses and corrected to formation temperature using Arps' equation (Arps, 1953). Lastly as for BVW, the values were obtained based on the function of PHIA and Sw. The summary of the parameters is in Table 3.

TABLE 3. Compiled and assumed petrophysical calculation values.

Parameters	Values	Methodology
Rw @ 77 F (ohm-m)	0.038 – 0.039 – 0.040	Water analysis report: NDIC 20043-24670-20043
Formation Temperature (degF)	238	DST report: NDIC 20043
Rw @ Formation Temperature (degF)	0.0100 - 0.0102 – 0.0105	Corrected from water analysis report
a	1	Regional/Pickett Plot
m	1.82 – 2.00	Pickett Plot; Regional
n	2	Regional/Pickett Plot
Salinity (mg/l)	298,735 - 290,760 – 301,859	Water analysis report: NDIC 20043-20043-24670
GR Max (API)	20	Red River 'D' Histogram key wells
GR Min (API)	4	Red River 'D' Histogram key wells
Limestone Density (g/cc)	2.71	Asquith et al. (2004)
Dolostone Density (g/cc)	2.87	Asquith et al. (2004)
Lithology	Kukersitic, burrow-mottled limestone/dolostone	Husinec (2016); Nesheim (2017a)

RESULTS

Perforation Records

OBSERVATION: Perforation records indicate that the Red River D interval has been the primary reservoir of the Red River wells from both the 2-D seismic and 3-D seismic phases of exploration and development. Examining Red River perforation records from all of the producing wells shows every productive well perforated at least a few feet of the D interval (Fig. 4). Meanwhile, only one well had perforations within the B interval and two wells had distinctive perforations within the C interval (the C-D interval boundary is not consistently well defined). Additionally, several of the more recent wells drilled and completed by Whiting Oil and Gas had perforations that extended below the D interval.

INTERPRETATION: The Red River D interval is the primary producing reservoir in the Red River Petroleum System within the study area to date.

Structural Closure

OBSERVATION: Based upon available well control and the 3-D seismic derived structure contour maps of the Red River Formation top provided by Whiting Oil and Gas, there is

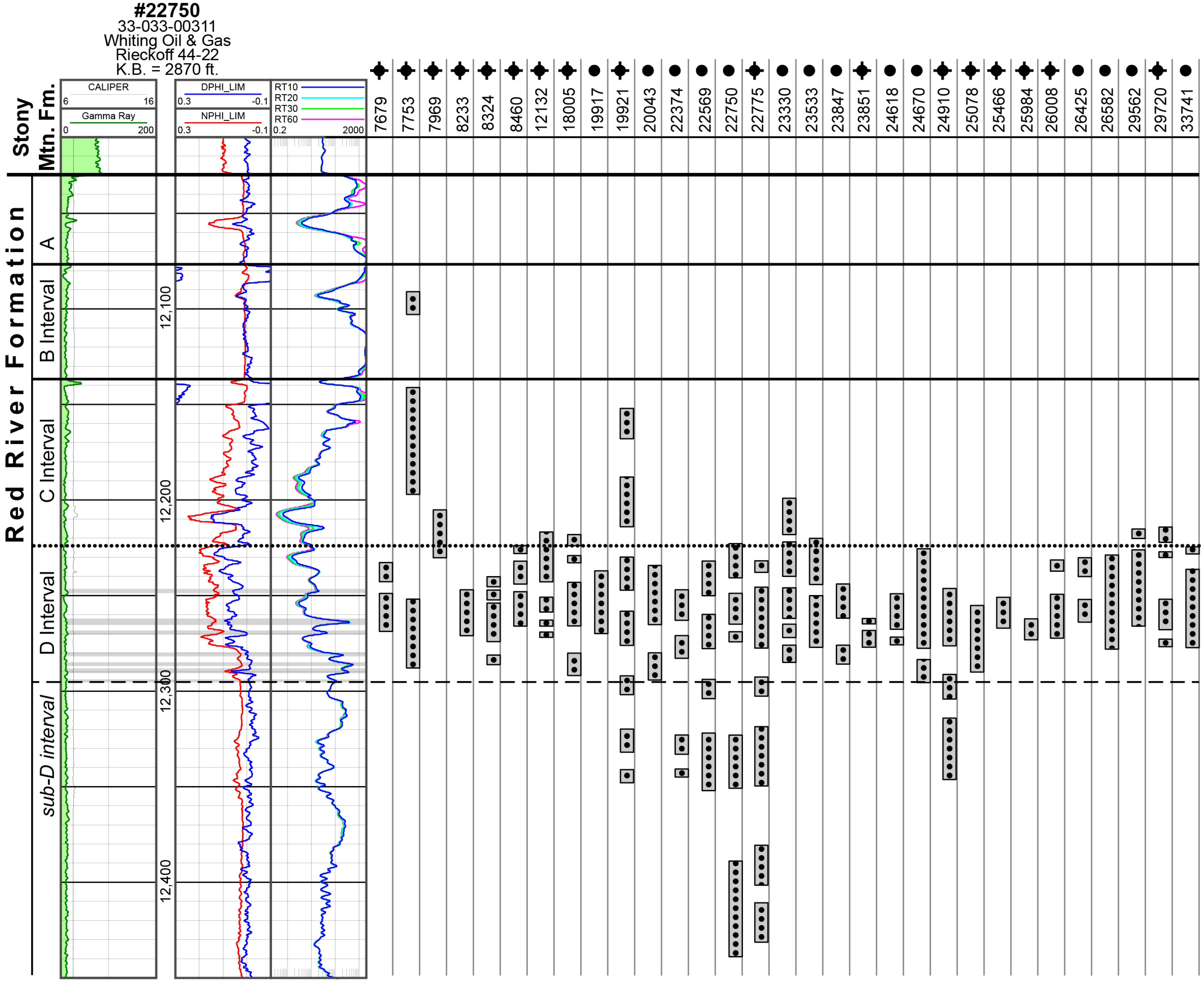


FIGURE 4. Compiled perforations from Red River productive oil and gas wells within the study area in relation to wireline logs from Whiting Oil and Gas's Rieckoff 44-22 (NDIC: 22750; API: 33-033-00311). Grey shaded intervals depict Red River kukersite beds (petroleum source rock).

minimal to negligible structural closure associated with many of the Red River productive wells (Fig. 5A). In fact, many of the best producing Red River wells in the Camel Hump Field are positioned within a subtle structural low.

INTERPRETATION: Structural closure does not appear to be a primary control on hydrocarbon accumulations and production for the Red River D interval within the study area.

Variable D Interval Porosity

OBSERVATION: Multiple 3-D seismic derived porosity maps have been submitted through oil and gas hearing that exhibit variable porosity in the Red River D interval (e.g. Figs. 5B-D). The seismic data is not publicly available for evaluation. However, wireline logs and core analysis data from Red River wells across the study area are publicly available and examined below.

Porosity logs across the Red River D interval reveal that most non-productive, dry holes consist of low porosity (<10%) limestone that is partly to completely non-dolomitized (neutron and density porosities set to a limestone matrix trend proximal to one another) (Fig. 6). Meanwhile, the productive Red River wells display high porosity (≥10%) consisting of mostly dolomite (neutron porosity extends to left of density porosity when both are set to a limestone matrix). One of the publicly available 3-D seismic-derived porosity maps includes a D interval productive well that displays good log porosity (well #29562 – Figs. 5C & 6), and a dry hole with low D interval porosity (well #8713 – Figs. 5C & 6).

Two adjacent wells in the Hoot Owl Field both have corresponding D interval cores with wireline logs and porosity-permeability data (Figs. 5-9). The D interval Peplinski 34-9 exhibits core measured porosity values of up to 17% and corresponding permeability values up to 14 millidarcies within a burrow-mottled dolo wacke-mudstone (e.g. Figs. 7-9). Meanwhile, the D interval burrow-mottled facies within the Schaal 22-15H is only partially dolomitized and reaches a maximum porosity of only 9% with corresponding permeability values all less than one millidarcy (Figs. 7-9). The Peplinski 34-9 has produced over 50 MBO to date while the Schaal 22-15H was essentially a dry hole.

Despite the variable dolomitization and reservoir development in the D interval, both cores contain the Red River kukersite petroleum source beds (Figs. 7 & 8). Tmax and Hydrogen Index values from the Peplinski 34-9 indicate the Red River is within the peak oil generation window (Nesheim, 2017a, b). Petroleum source rock net thickness variations appear to be minimal between the two cores.

A positive relationship between core-plug measured grain density and porosity reflects that dolomitization is the primary control on reservoir quality in the D interval. Between the grain density range of 2.71 and 2.83 g/cm^3, porosity increases with grain density (Fig. 9A). This relationship reflects that increasing dolomitization develops more porosity within the D interval burrow-mottled facies. After reaching the parameters of approximately 2.83

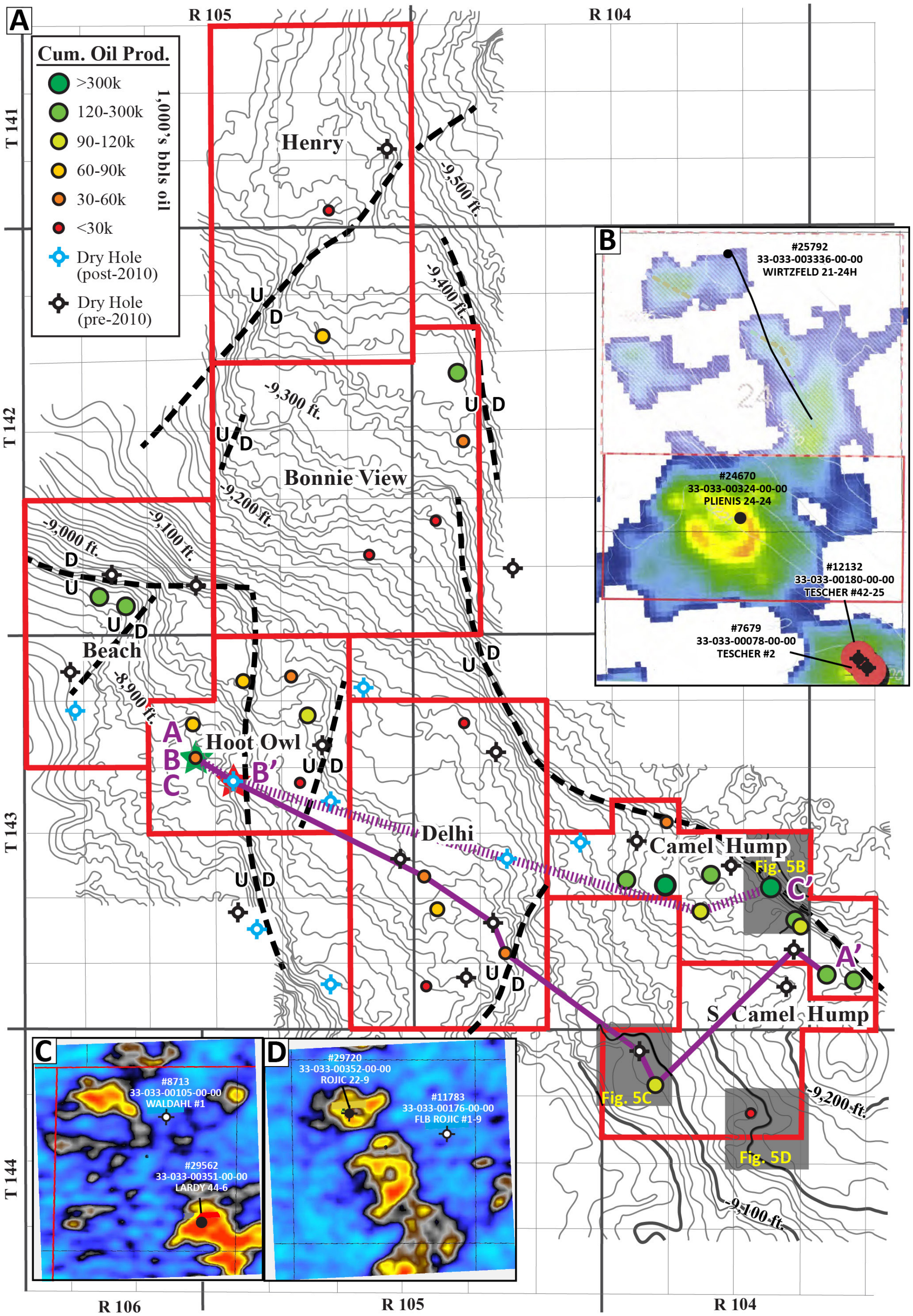


FIGURE 5. Compilation of 3-D seismic derived maps submitted as publicly available NDIC Oil and Gas Hearing exhibits: **A)** structure contours on the Red River Formation top, B-D) amplitude anomaly maps of the Red River D interval displaying interpreted high porosity (**5B:** green-yellow-orange, and **5C-D:** yellow-orange-red) versus low porosity development (**5B:** white-blue, and **5C-D:** blue) within portions of the Camel Hump and South Camel Hump Fields. Thick dashed black lines indicate interpreted faults based upon the 3-D seismic derived Red River Formation top structure contours.

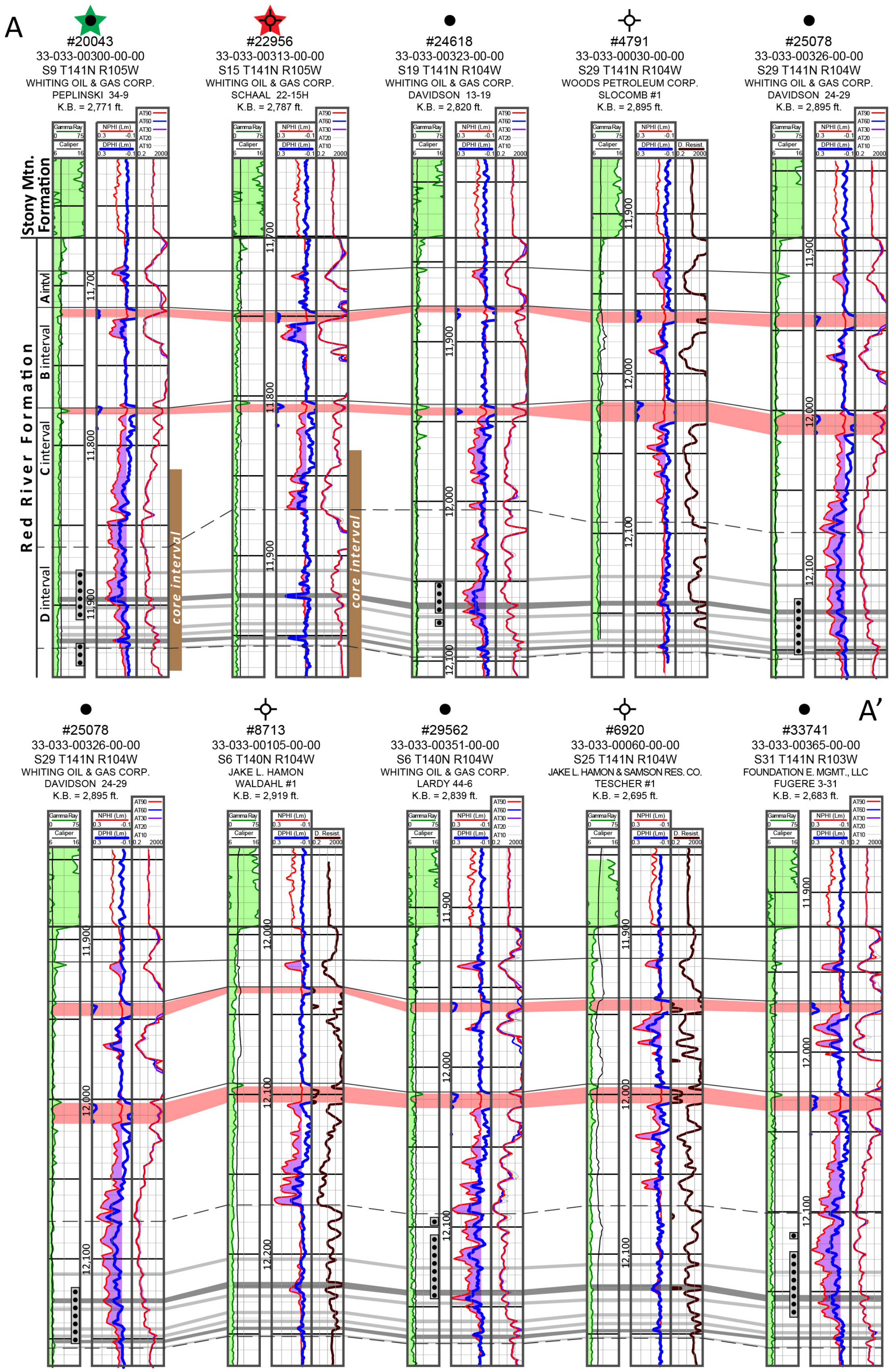


FIGURE 6. Wireline log cross-section of the upper Red River Formation oriented northwest to southeast that alternates between productive oil wells and dry holes. Neutron porosity (limestone matrix) is shaded purple. Grey shaded intervals depict Red River kukersite beds (petroleum source rock).

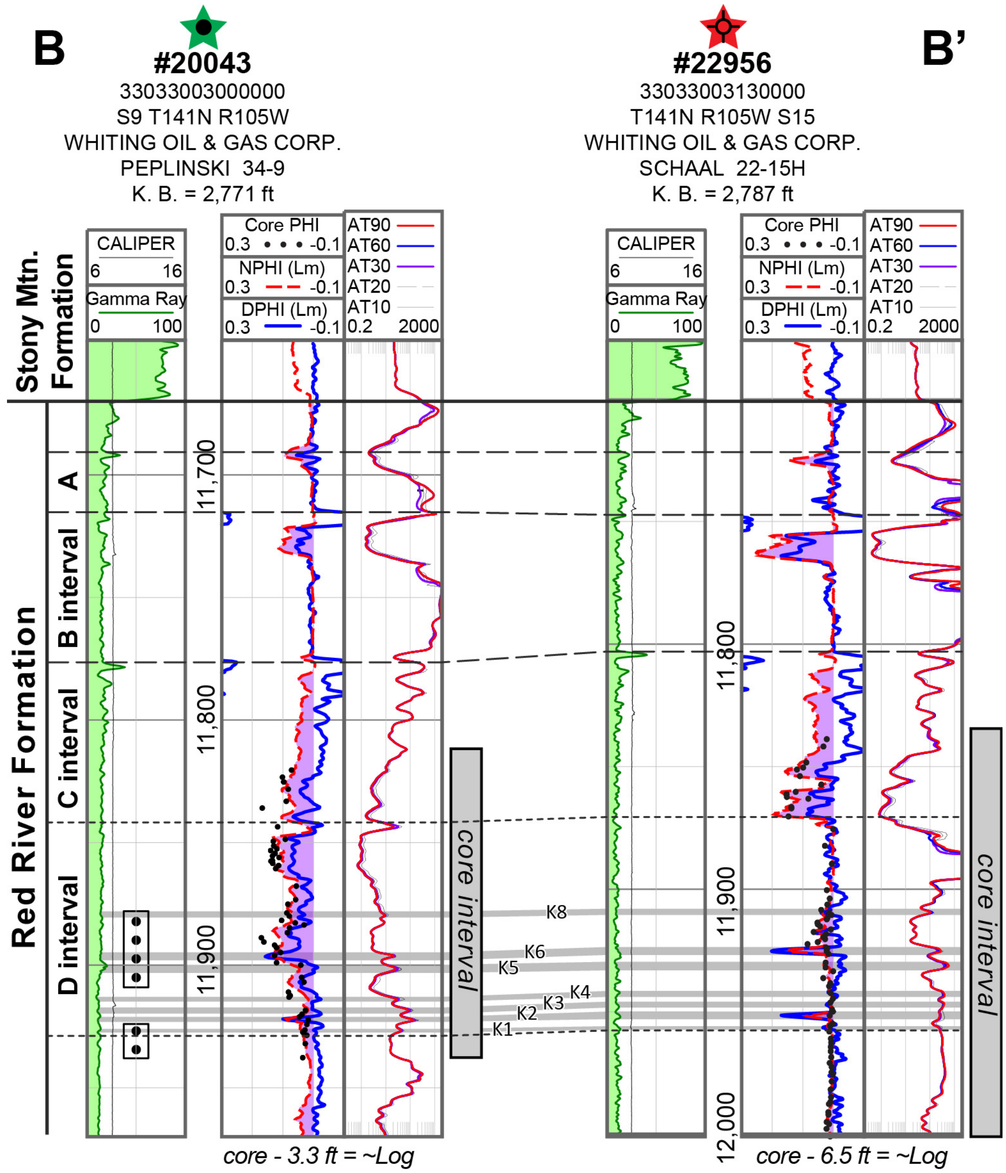


FIGURE 7. Wireline log cross-section of the upper Red River Formation with core-plug porosity data from Whiting Oil and Gas Corporation's Peplinski 34-9 and Schall 22-15H wells. Grey shaded intervals depict Red River kukersite beds (petroleum source rock).

g/cm^3 and 9% porosity, grain density remains around 2.83 g/cm^3 while porosity varies, reaching upwards of ~21% within the available core data (Fig. 9A). While dolomitization of the burrow-mottled facies appears to be the primary component to developing reservoir in the D interval, other factors such as the bioturbation intensity and/or style of burrowing likely play secondary roles in reservoir quality.

A positive correlation occurs between core-plug porosity and permeability within the D interval of the study area (Fig. 9B). All of the core-plug porosity values of <9% porosity have corresponding permeability values of <1 millidarcy (Fig. 9B). Meanwhile, most of the samples with ≥9% porosity have corresponding permeability values ranging from 1 to 40 millidarcies (Fig. 9B).

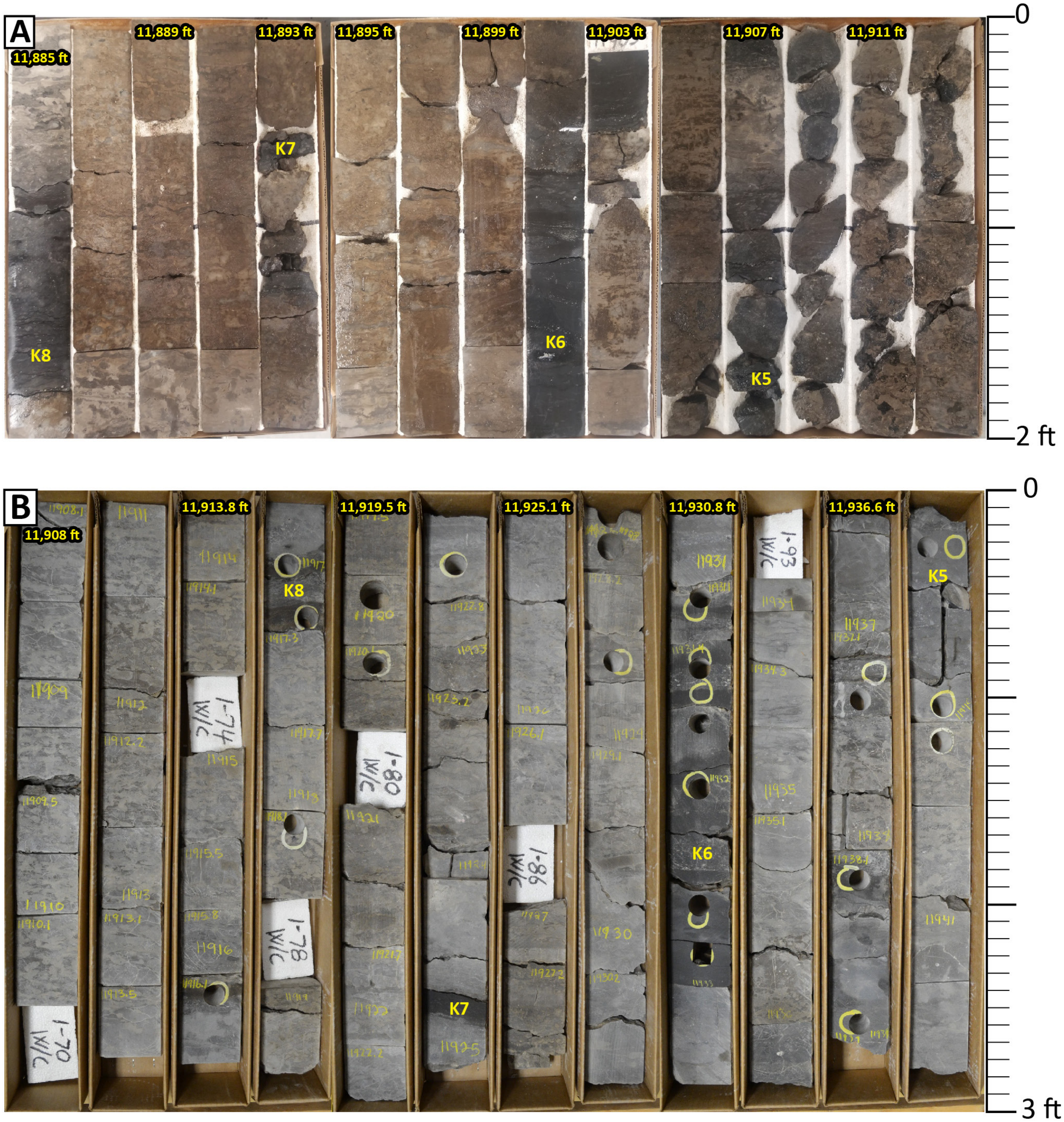


FIGURE 8. Tripod core photographs from the Red River D interval: **A)** highly porous dolomitized burrow-mottled wacke-mudstone with interbedded kukersite source beds (K5-K8), and **B)** marginally porous, partially to non-dolomitized burrow-mottled lime wacke-mudstone with interbedded kukersite source beds (K5-K8).

INTERPRETATION: Dolomitization of the burrow-mottled facies in the D interval appears to be the primary control on reservoir quality. Partially to non-dolomitized burrow-mottled facies exhibit porosity values of <1-9% porosity with permeability <1 mD while fully dolomitized burrow-mottled facies have porosity of 9-21% and permeabilities of typically

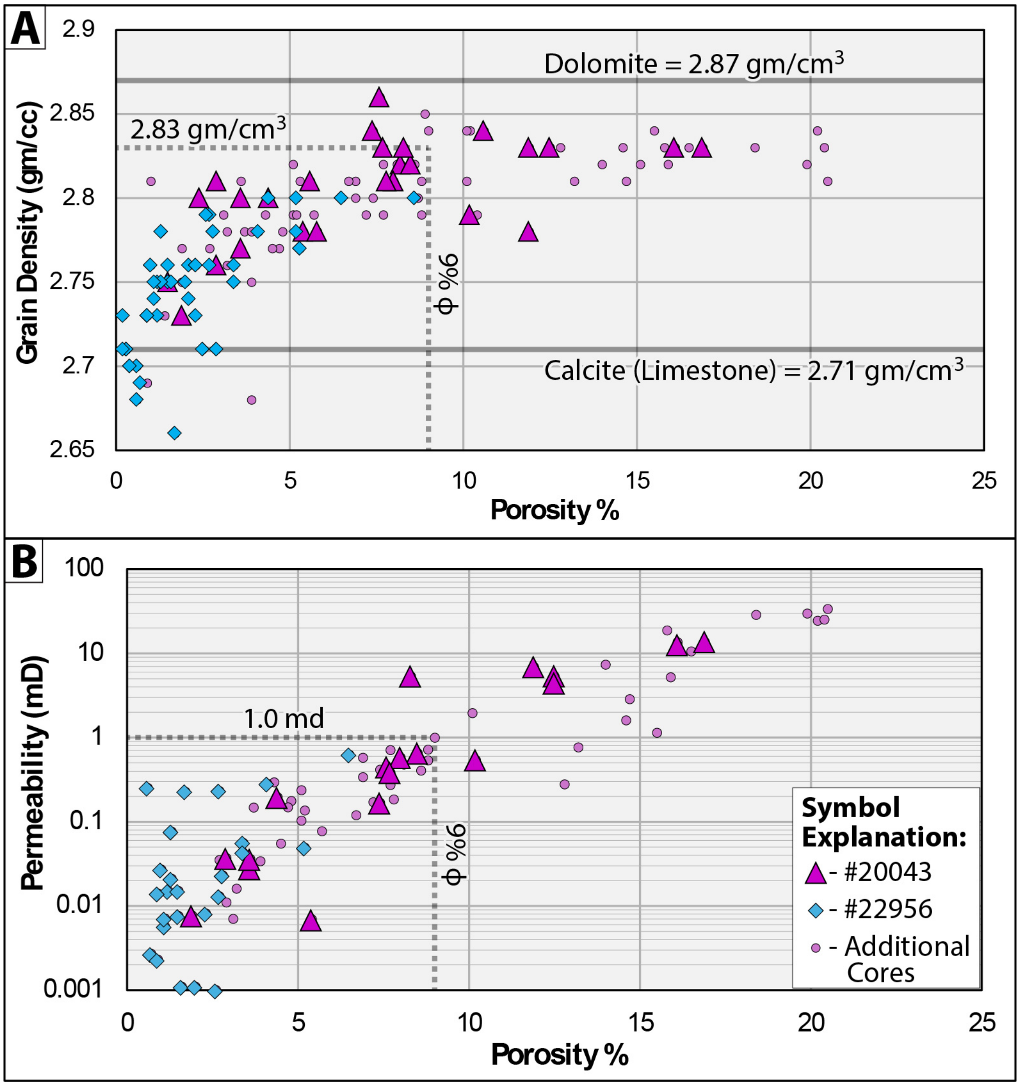


FIGURE 9. Compiled core-plug analysis data from Red River D interval cores within the study area. **A)** Cross-plot of grain density versus porosity, and **B)** porosity versus permeability (Klinkenberg).

1-40 millidarcies. Porosity values of >9% appears to be required to reach fair quality permeability values of one millidarcy or greater. Many of the Red River dry holes contain minimal to negligible burrow-mottled facies with porosity values of 9% or greater while the producing wells contain tens of feet of porous dolomitized burrow-mottled facies.

Preliminary Petrophysical Analysis

OBSERVATION: Even when dolomite porosity is moderately to well developed in the Red River D interval, production results in the study area are variable. Preliminary petrophysical analysis was conducted within the Red River D interval on select wells representing dry, moderate, and highly productive wells to understand the possible controls on reservoir quality and fluid distribution. The wells used are as follows: #20043, #25240, #26582, and

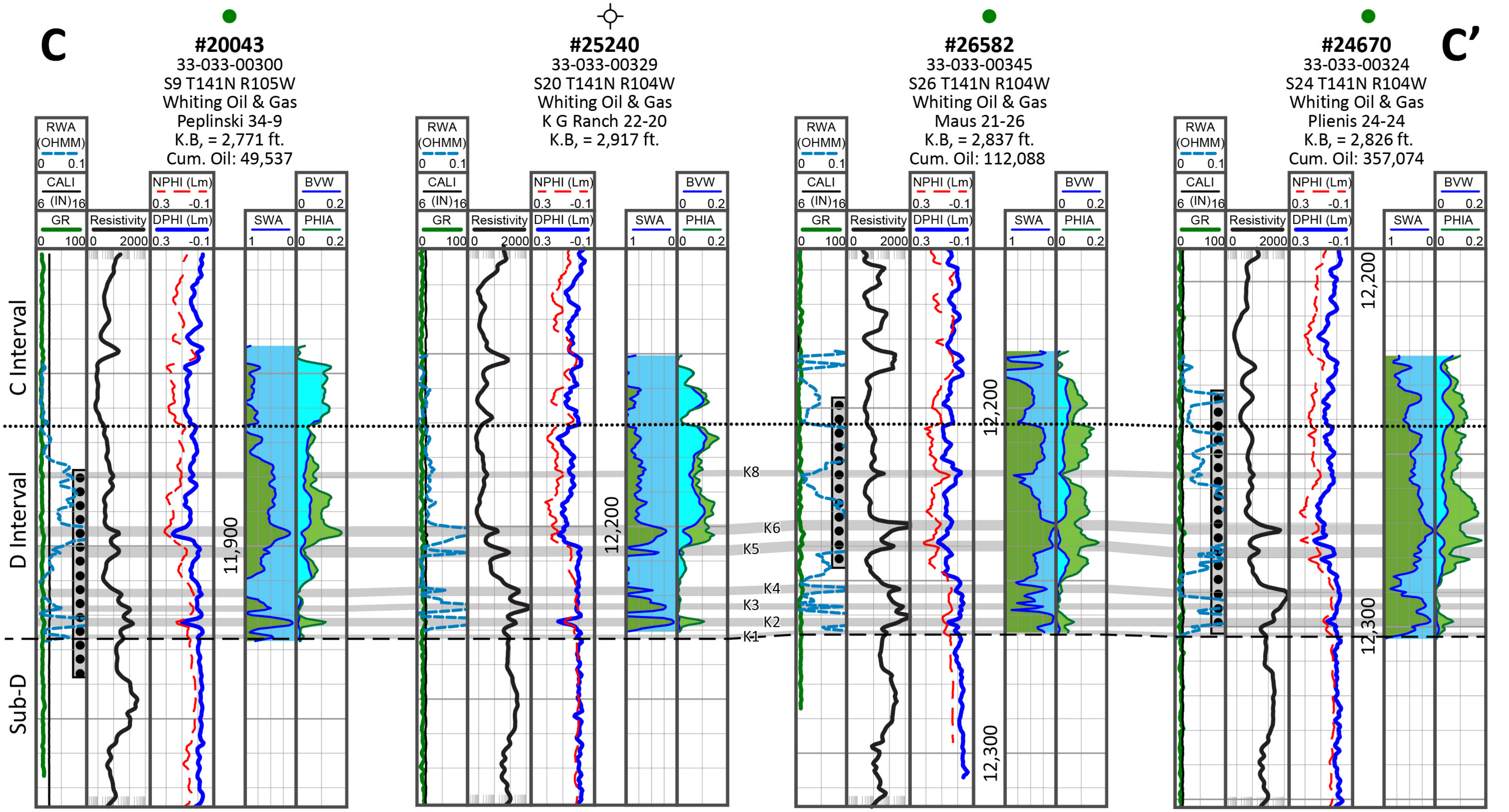


FIGURE 10. Wireline log cross-section of the Red River D interval with preliminary petrophysical logs. BVW = bulk volume water calculated combining PHIA and SW log values; PHIA = average of neutron and density porosity, both on a limestone matrix; SWA = water saturation calculated with Archie equation. Grey shaded intervals depict Red River kukersite beds (petroleum source rock).

#24670 (Fig. 10, Table 2). The more productive wells (#26582 and #24670) exhibit higher overall porosity across the D interval than the moderately productive well (#20043) and the dry hole (#25240) (Fig. 10). A cross plot of core porosity versus permeability, colored by core water saturation, indicates that intervals with Sw <60% and permeability >1mD consistently correspond to core porosity above 8% (Fig. 11a). When tied to the cross plot of core porosity versus log-derived PHIA, this supports a PHIA cut-off of approximately 8.5% - 9% (Fig. 11b).

As for Archie-derived water saturation (Sw), the more productive wells (#26582 and #24670) show Sw generally <45%, the moderate well (#20043) displays Sw values between 60% – 70%, and the dry well (#25240) shows high Sw (>70%) across intervals with negligible porosity, aside from several log porosity spikes associated with kukersite source beds (Fig. 10). Additionally, the productive well exhibits relatively low and stable BVW (approximately 0.02 – 0.03), the moderate well shows elevated and variable BVW (>0.035), and the dry wells demonstrate high variation of BVW across the interval (Fig. 10).

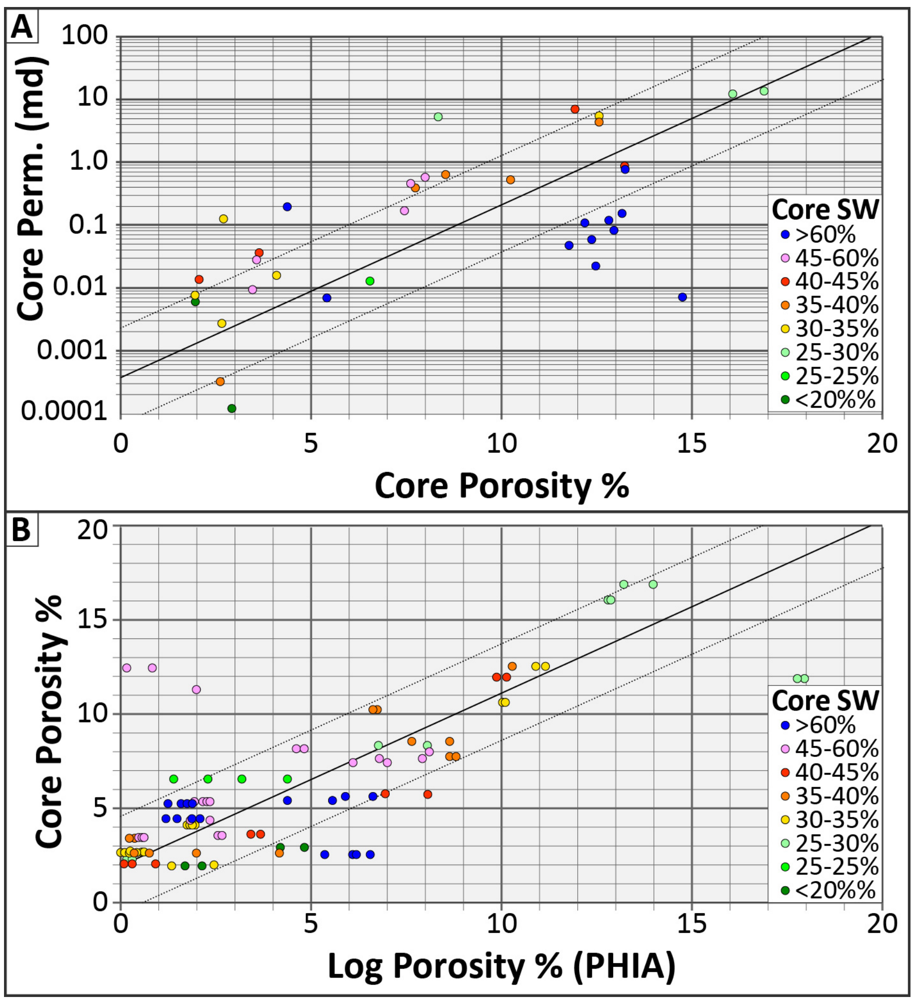


FIGURE 11. Core porosity versus log porosity (PHIA = average of neutron and density porosity, both on a limestone matrix) for select Red River wells from the study area. Core SW = core-plug water saturation.

The more productive wells such as #26582 and #24670 (~117 MBO & ~384 MBO – Table 2) display relatively high PHIA with relatively low Sw and BVW (Fig. 10), which supports the presence of a hydrocarbon-charged reservoir. Conversely, the dry (non-commercial) well, NDIC #25240, shows relatively high porosity suggesting potential reservoir interval, but elevated Sw and BVW indicate the reservoir is water wet. Meanwhile, #20043 has been moderately productive (50 MBO – Table 2) and exhibits PHIA that is slightly lower, with Sw and BVW are slightly higher, than the more productive wells (#26582 and #24670).

INTERPRETATION: Despite multiple wells targeting similar Red River D porosity pods identified through 3-D seismic, the PHIA, Sw, and BVW values are variable and directly influence production outcomes. The petrophysical evaluation results show high conformance between reservoir quality and production performance. Wells with higher cumulative oil production consistently correspond to intervals with higher PHIA, lower Sw, and lower BVW (e.g. Fig. 10 - wells #26582 and #24670). Therefore, while dolomite porosity development in the D interval is a primary factor in establishing commercial production, the overall quality of the dolomite reservoir and hydrocarbon charge are additional important components.

Faulting

OBSERVATION: Several of the 3-D seismic Red River wells that ranged from marginally oil productive wells (<30 MBO) to dry holes (yielded ~100% water) are positioned near interpreted faults that trend southwest-northeast, parallel to the dip of the Red River Formation top (Fig. 5). Meanwhile, the more productive Camel Hump and Beach Field wells are positioned up-dip from faults, which trend approximately northwest-southeast, perpendicular to the dip of the Red River Formation top (Fig. 5).

INTERPRETATION: Faults that crosscut/breach the Red River D interval porosity zones may cause partial to complete leakage of locally produced hydrocarbons (Fig. 12a). Meanwhile, faults positioned downdip from the more productive wells may provide additional hydrocarbon charge through short distance hydrocarbon migration (Fig. 12b). Fault throw and size may also play a role in adding or removing (leaking) hydrocarbon charge.

Hydrocarbon Thermal Maturity

OBSERVATION: Both the API oil gravity and GOR's of Red River D interval hydrocarbon production increase towards the southeastern corner of the study area (Camel Hump Field). The API oil gravity increases from <28° in the west-northwest portions of the study area to over 32° in the southeastern corner (Camel Hump Field) (Fig. 13). GOR values are more variable but reach values as low as 0.05 MCF gas per barrel of oil towards the west and increase to values consistently between 0.32 and 0.65 within the Camel Hump Field (Fig. 13).

INTERPRETATION: API oil gravity and GOR of produced hydrocarbons from the D interval trend with the kukersite source beds thermal maturity (Nesheim, 2017a). Therefore,

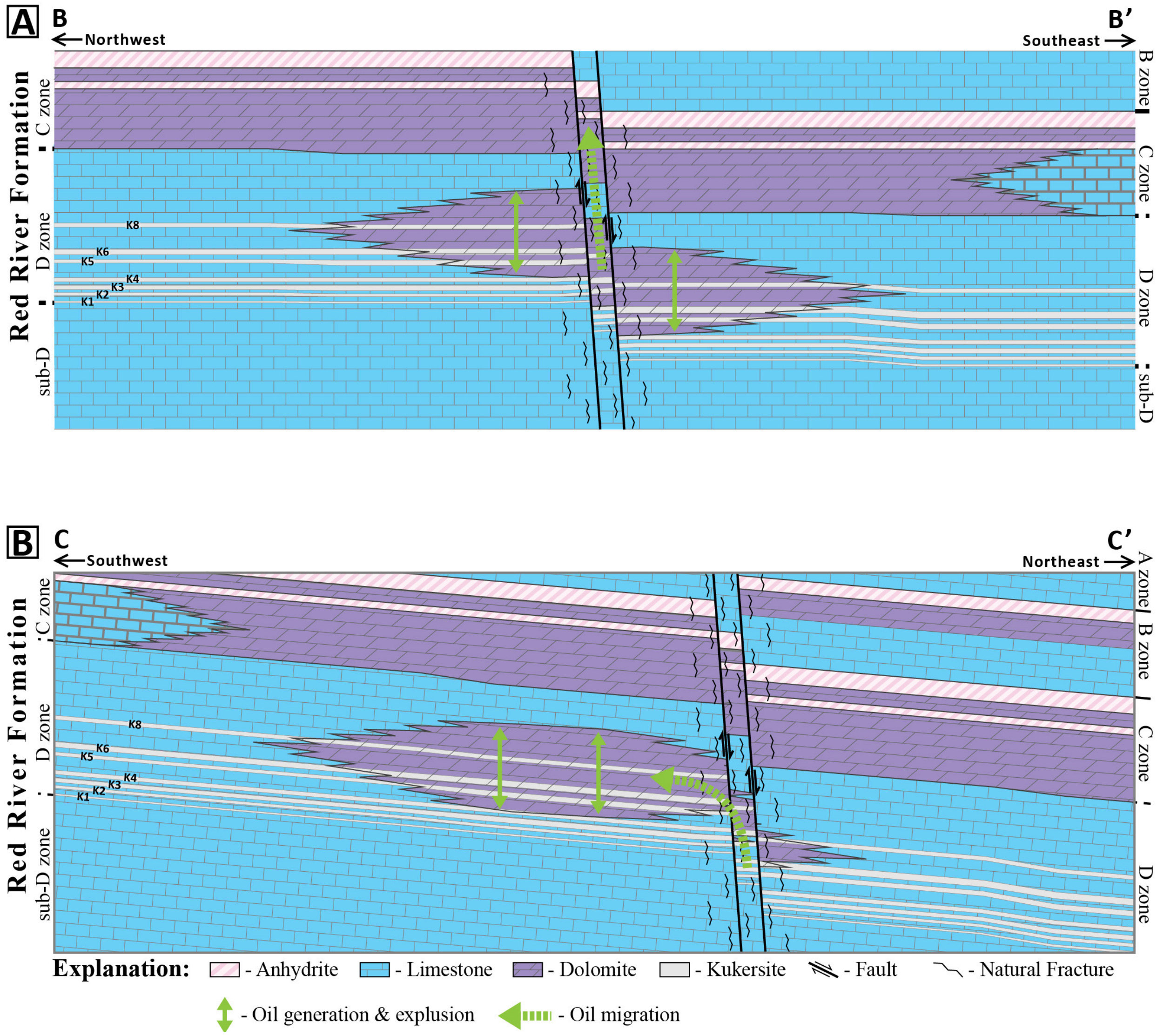


FIGURE 12. Schematic cross-sections depicting hypothesized relationship between faulting and hydrocarbon charge in the Red River D interval. **A)** Cross-cutting fault oriented parallel to dip that results in partial to complete leakage of locally generated hydrocarbons out of the D interval porosity pod. **B)** Down-dip fault-oriented perpendicular to regional dip that results extra up-dip migrating hydrocarbon charge.

higher gravity oil and GOR indicate that the source beds are more thermally mature with respect to hydrocarbon generation and more hydrocarbons have been generated per unit area within the Camel Hump Field than in the lower maturity western fields. The greater the volumes of generated hydrocarbons equate to potentially more prospective in-place resource and better production results assuming limited lateral hydrocarbon migration.

Additionally, the more mature hydrocarbons may increase the overall effective drainage of the reservoir. Higher API oil gravity has a smaller molecule size and lower viscosity than lower gravity oil and may move more easily through a reservoirs pore system. Higher GOR indicates more gas dissolved in the reservoir oil which would also flow more readily through pore systems than oil with lower GOR (higher gas drive).

Camel Hump Field

Camel Hump Field has yielded nine of the thirteen wells in the study area that have cumulatively produced >100 MBO. A northwest-southeast trending down-dip fault extends through northeastern Camel Hump Field, downdip of the productive wells (Fig. 5). Camel Hump wells also consistently yield oil with >32° API gravity and GOR values of between 0.3 and 0.7 MCF/BO (thousand cubic feet of gas per barrel of oil) (Fig. 13).

Meanwhile, the Hoot Owl and Delhi fields have yielded mostly marginally productive wells (<60 MBO) and dry holes. Interpreted faults that are oriented approximately north-south extend through the Hoot Oil and Delhi fields, which are proximal to dry holes drilled with 3-D seismic as well as marginal (<60k MBO) to intermediate wells (60-90 MBO) (Fig. 5). Most of the dry holes drilled with 3-D seismic are located within or proximal to the Hoot Owl and Delhi fields (Fig. 5). Additionally, the produced hydrocarbons consist of oil that is <32° API gravity with associated GOR values that are typically <0.30 MCF/BO (Fig. 13).

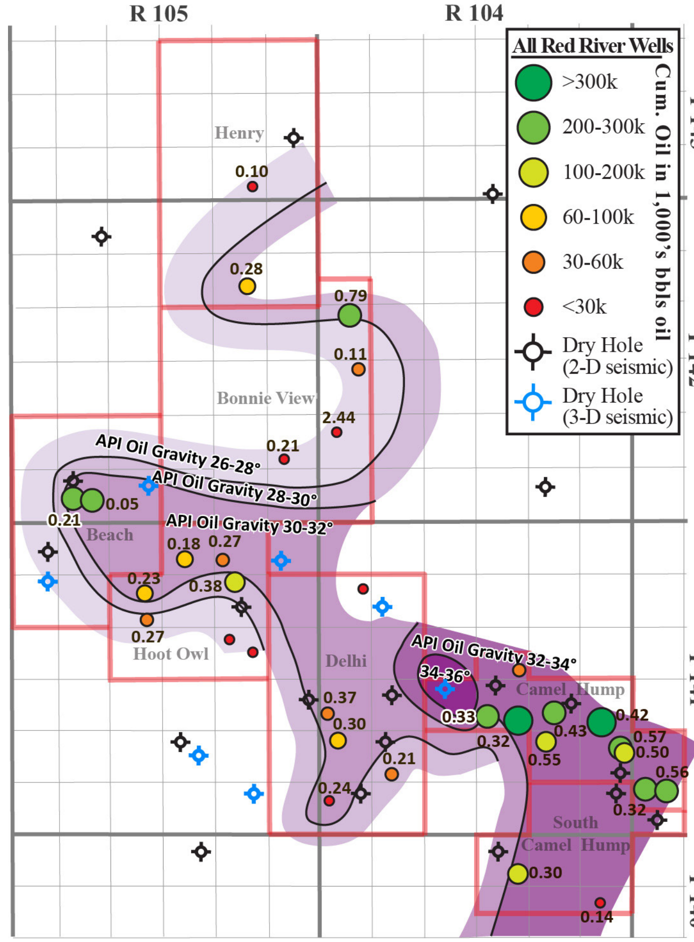


FIGURE 13. Field map of the study area depicting the API oil gravity (purple shaded contours) and initial Gas to Oil Ratios (numbers next to each productive well: MCF gas/BBLS oil) of Red River C and D interval produced hydrocarbons.

Future Exploration

Nesheim (2017b) noted that southwestern North Dakota could represent a potentially under-explored and underdeveloped acreage position within the Red River Petroleum System. Thermally mature Red River petroleum source beds extend throughout a large area in southwestern North Dakota which contains multiple scattered Red River oil producers but an overall low well density compared to the size and distribution of the seismic-derived porosity pods in the study area (Figure 14). Additionally, numerous Red River oil producing wells occur both downdip (north) and up dip (south) of this area, further indicating the potential of this prospective exploration fairway.

While publicly available seismic data is unavailable to evaluate subsurface distribution of porosity development in the Red River D interval, several dozen wireline logs throughout the interval are available to make a preliminary evaluation. As displayed on Figure 15, porosity varies from being consistently <5% to reaching upwards of ~15-20% across the D interval in southwestern North Dakota while the Red River kukersite source beds appear to be continually present. The wireline log well density is too low to definitively state if stratigraphic trapping of D interval hydrocarbons occurs across part or all of the area of interest in southwestern North Dakota, but is encouraging based upon available data.

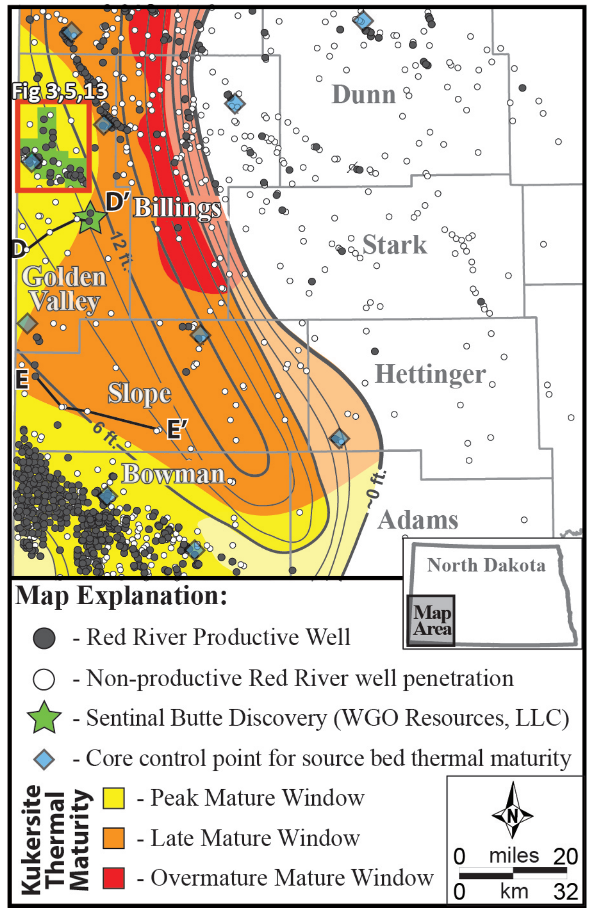


FIGURE 14. Map of southwestern North Dakota displaying Red River Formation well penetrations and producers along with Red River kukersite (petroleum source bed) net thickness and interpreted thermal maturity. C-C′ and D-D′ depict the location of the Figure 15 cross-sections. Red outline depicts the primary study areas.

Recent Activity

In late 2024, the Koon Harkins 1-35 (NDIC: 41017, API: 33-033-00369-00-00) and Koon Harkins 1-26 (NDIC: 41018, API: 33-033-00370-00-00) were drilled by WGO Resources, LLC targeting the Red River D interval using 3-D seismic (NDIC Case #31414 and #31486). Both wells were completed as successful oil producers with perforations in the Red River D interval and represent the discovery wells of the Sentinel Butte Field (Fig. 14 and 15, D-D′ well #41017). The Koon Harkins wells and the Sentinel Butte Field discovery represent the first southwards expansion of the Red River D interval play from the Beach-Camel Hump Field area.

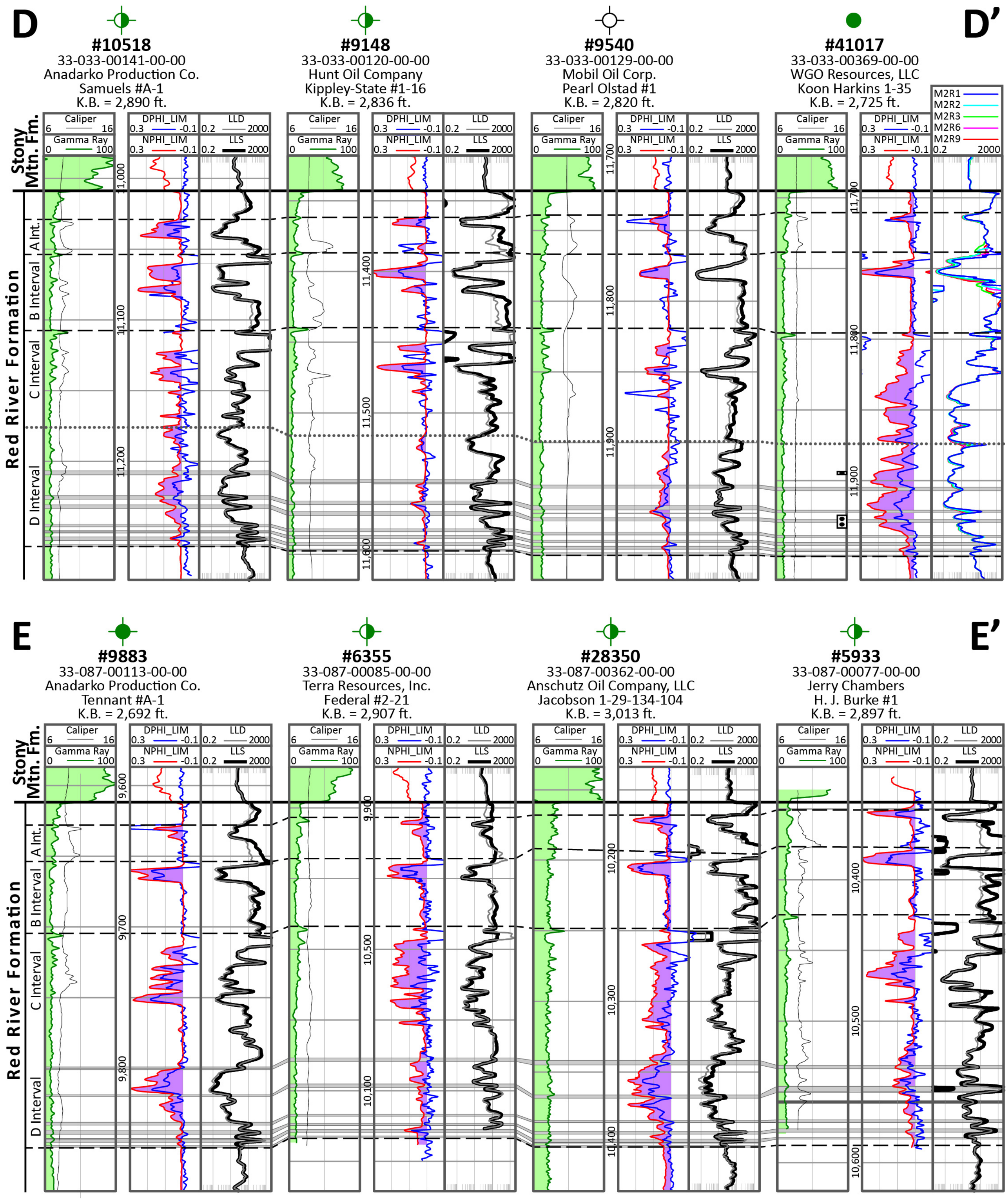


FIGURE 15. Cross-sections of the upper Red River Formation in southwestern North Dakota displaying the interpreted lateral continuity of the Red River kukersite petroleum source beds and the discontinuous dolomite porosity development within the D interval. The cross-section well locations are displayed on Figure 14. Grey shaded intervals depict Red River kukersite beds (petroleum source rock).

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