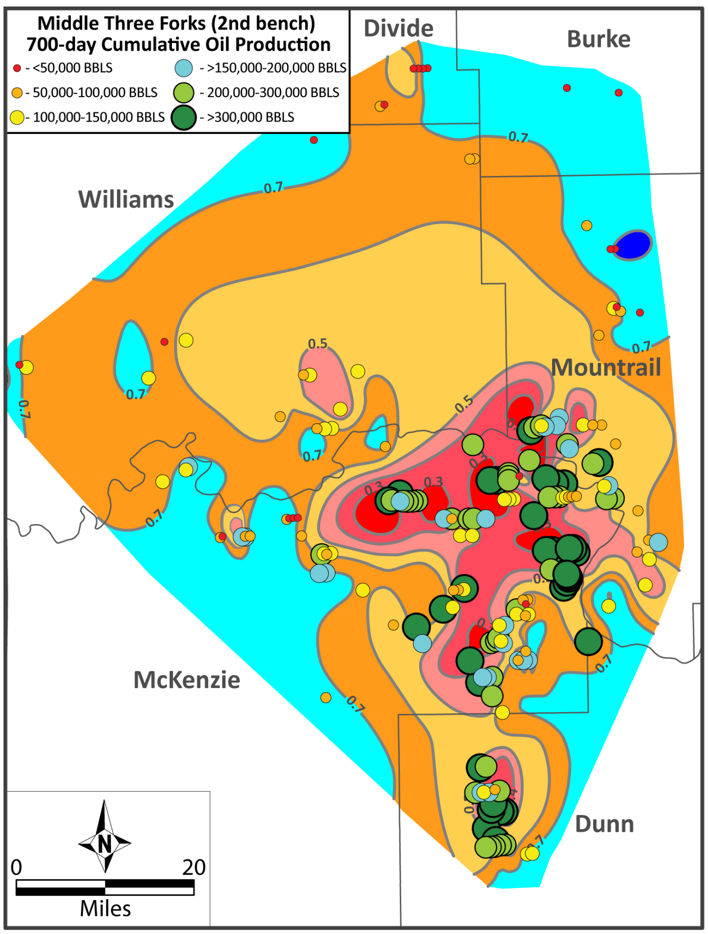
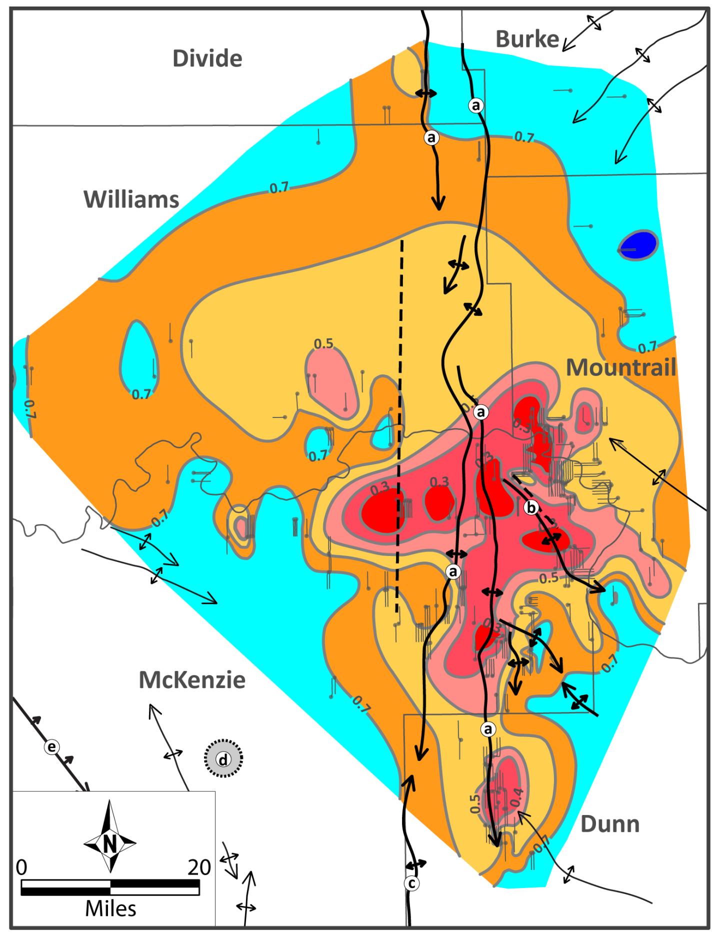
Evaluation of Water-Cuts from Middle and Lower Three Forks Production (2nd and 3rd benches): Western North Dakota

Timothy O. Nesheim





GEOLOGIC INVESTIGATION NO. 245
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2020

TABLE OF CONTENTS

FIGURES

TABLE

INTRODUCTION

Commercial oil and gas production from horizontal wells drilled and completed within the middle and lower Three Forks Formation (Three Forks) began in early 2013 (Nesheim, 2020a, 2021). Since that time, more than 300 horizontal wells have been drilled and completed between both units (Figs. 1 and 2). Cumulative production from the middle and lower Three Forks wells totals more than 63 million barrels of oil and 120 billion cubic feet of gas (Nesheim, 2020a, 2021). Elevated core-plug oil saturations across the Three Forks section have been previously linked to increased thickness and thermal maturity of the Lower Member of the Bakken Formation (Bakken), which is an organic-rich, black shale (Nesheim, 2019). These spatial relationships indicate that the Lower Member of the Bakken is the primary source of Three Forks hydrocarbons (Nesheim, 2019). Furthermore, hydrocarbon charge from the Lower Bakken to the Three Forks appears to have occurred with limited to minimal lateral migration within the central portions of the Williston Basin in which hydrocarbons were forced downwards on the order of 10's to 100's of feet (Nesheim, 2019).

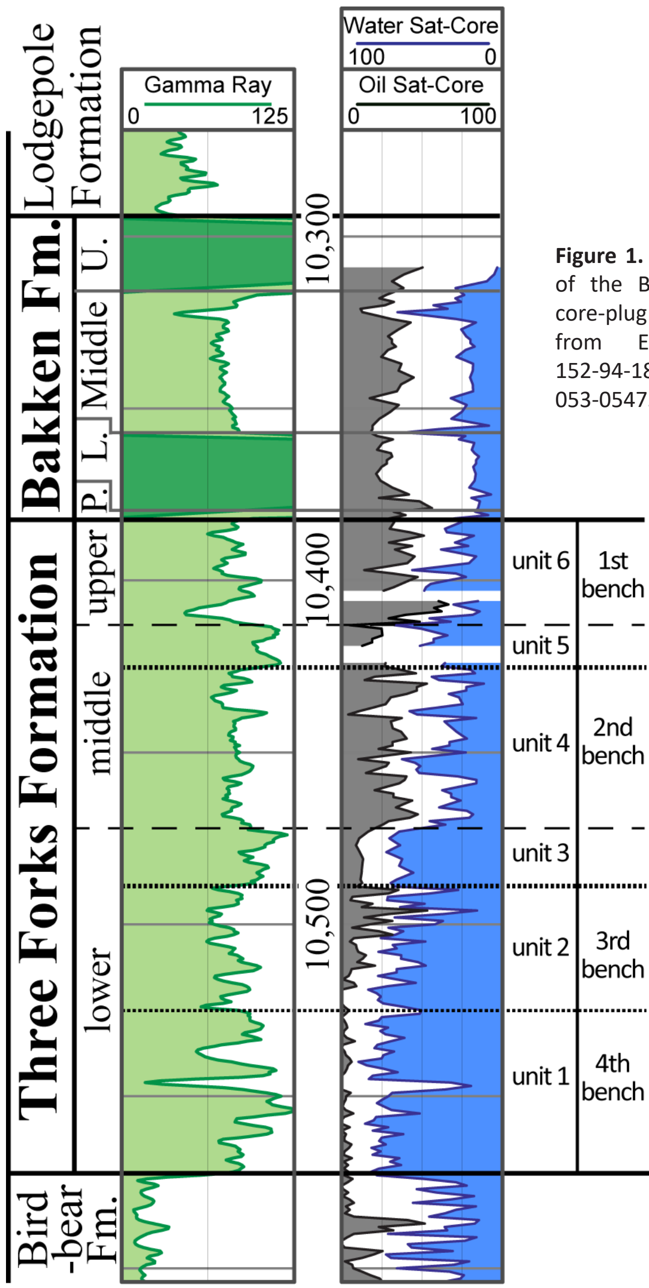


Figure 1. Gamma-ray wireline log example of the Bakken-Three Forks section with core-plug oil and water saturation data from Enerplus Resource's Hognose 152-94-18B-19H-TF (NDIC: 26990; API: 33-053-05475-00-00).

Figure 2. Horizontal well location map for the middle (A) and lower (B) Three Forks Formation. Well lists were extracted from Nesheim (2020b). The yellow stars indicate NDIC well #26990 from Figure 1.

The water-cut of an oil well represents the volumetric ratio of produced water versus total fluids (oil + water) and generally represents the free-fluid ratio of a given reservoir. Water-cut is one valuable characteristic of a hydrocarbon reservoir that can be utilized to spatially differentiate more oil-productive versus less oil-productive areas within a given oil play. The purpose of this report was to construct water-cut contour maps for the middle and lower Three Forks production to compare with previously published petroleum geology related information from the units and assist projecting future well development in the Williston Basin.

METHODS

Middle and lower Three Forks wells evaluated for this study were extracted from Nesheim (2020b), which generated a list of validated middle and lower Three Forks horizontal wells. In review, middle Three Forks wells are defined as horizontal wells that were drilled primarily within the middle to lower portions of the middle Three Forks as defined by Bottjer et al. (2011), which is approximately equivalent to unit 4 from Christopher (1961, 1963) and the 2nd bench as referred to by some operators. Lower Three Forks wells are defined as horizontal wells that were drilled primarily within the middle/upper portions of the lower Three Forks, the interval which is approximately equivalent to the unit 2 of Christopher (1961, 1963) and the 3rd bench as referred to by some operators.

A multi-step process was utilized to 1) identify middle and lower Three Forks wells with reliable fluid production data and 2) calculate average water-cut values. First, wells with less than 540 cumulative production days (18 months) were removed. Diagrams plotting calculated monthly water-cut values were examined by individual well to determine if an approximate 1-year (365 day) phase of relatively stabilized water-cut was achieved between 0.5 and 4.0 production years for the well (Fig. 3). An approximate average 1-year (~365 day) water-cut was calculated for each well meeting these criteria. For most wells evaluated, monthly water-cuts stabilized within 6 months to 1 year after initial completion (Fig. 3A). For a lesser number of wells, monthly water-cut values did not stabilize until later in production and the approximate 1-year average water-cut was extracted during the 3rd and/or 4th years of production (Fig. 3B). Also, some productive middle Three

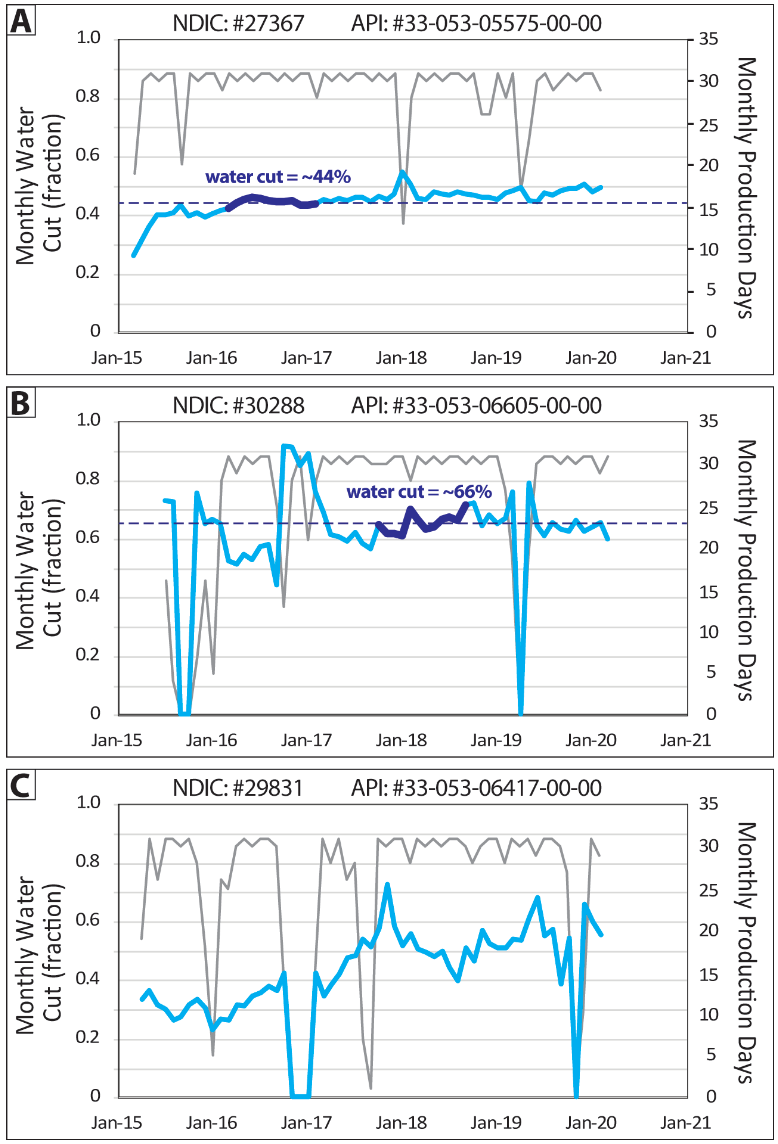


Figure 3. Examples of middle Three Forks production monthly water-cut (blue lines) diagrams. A) Example of a consistent, well defined middle Three Forks water-cut in which the 2nd year of production was utilized to calculate an average water-cut. B) Example of a well with variable initial 2-year water-cut rates in which the 3rd production year was used to calculate the water-cut. C) Example of a productive middle Three Forks well with a highly variable water-cut that was not included in the water-cut analysis map. Dark blue lines represent the time period averaged for water-cut analysis.

Forks wells with >540 cumulative production days have not yielded a prolonged (~1 year), stabilized monthly water-cut phase, or appeared to semi-stabilize during separate time phases but at substantially different value ranges (Fig. 3C). Such wells were not used for water-cut calculations and mapping purposes. Water-cut was then contoured separately for the middle and lower Three Forks using a combination of the contouring function in the map module of Petra© and manual editing (Fig. 4). Lastly, water-cut contours were compared with previously published geologic maps and structures.

RESULTS

A total of 221 middle Three Forks horizontal wells were identified with a minimum of 480 days of cumulative production that achieved a 1-year phase (~365 days) with a relatively stabilized water-cut during the first four years of production (Table 1). Calculated average water-cut values by well ranged from 6% to 94% with an average of 52%. Based on contour mapping, the largest area of reduced water-cut (most oil-prone) area is located within northeastern McKenzie County and extends slightly into southwestern Mountrail County, in which water-cuts are less than 50% and can reach as low as ~6% (Fig. 4, Table 1). Most of the horizontal middle Three Forks wells drilled and completed to date are located either within or proximal to this northeastern McKenzie-southwestern Mountrail County, low water-cut area. Two smaller low water-cut areas defined by multiple wells are also located in south-central Williams and northwestern Dunn counties (Fig. 4). Overall, water-cut increases radially outward across the study area, reaching intermediate values of 50-70% before climbing above 70% towards the outer portions of the study area (Fig. 4).

A total of 33 lower Three Forks horizontal wells were identified with a minimum of 480 days of cumulative production that achieved a 1-year phase (~365 days) with a relatively stabilized water-cut during the first four years of production (Table 1).

Table 1. middle and lower Three Forks water-cut and 700-day cumulative oil productic

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
22820	33053041010000	MTF (unit 4)	0.2672	1	708	352,320
23794	33053043930000	MTF (unit 4)	0.6892	1	703	69,443
24060	33025019070000	MTF (unit 4)	0.5532	3	712	66,708
24223	33025019530000	MTF (unit 4)	0.2421	2	704	215,551
24282	33025019650000	MTF (unit 4)	0.3573	2	693	162,381
24286	33025019690000	MTF (unit 4)	0.4367	2	712	145,217
24289	33105028720000	MTF (unit 4)	0.6079	2	712	104,821
24376	33105028900000	MTF (unit 4)	0.6161	2	691	103,978
24378	33105028920000	MTF (unit 4)	0.4738	2	711	147,056
24456	33025020070000	MTF (unit 4)	0.2744	2	703	156,791
24473	33053046190000	MTF (unit 4)	0.2153	1	690	231,384
24494	33105029210000	MTF (unit 4)	0.7171	1	713	36,062
24578	33105029300000	MTF (unit 4)	0.4949	2	696	87,186
24594	33023009650000	MTF (unit 4)	0.6367	1	709	56,283
24607	33105029390000	MTF (unit 4)	0.7077	2	687	78,837
24611	33105029430000	MTF (unit 4)	0.6970	2	689	114,006
24658	33023009770000	MTF (unit 4)	0.7126	1	694	44,943
24791	33053047240000	MTF (unit 4)	0.8302	2	707	40,818
24802	33053047290000	MTF (unit 4)	0.5390	2	710	109,789
24804	33053047300000	MTF (unit 4)	0.8052	2	612	25,270
24808	33053047340000	MTF (unit 4)	0.8453	3	711	20,530
24812	33053047370000	MTF (unit 4)	0.2984	2	697	135,747
24837	33053047440000	MTF (unit 4)	0.6356	1	706	75,597
24842	33053047470000	MTF (unit 4)	0.7630	1	699	41,244
24908	33053047690000	MTF (unit 4)	0.6289	2	689	61,302
24924	33023009960000	MTF (unit 4)	0.5958	2	707	44,161
24930	33023009990000	MTF (unit 4)	0.6905	1	704	41,943
24964	33023010040000	MTF (unit 4)	0.7186	1	711	38,153
24966	33023010060000	MTF (unit 4)	0.7395	2	707	40,033
25511	33105030620000	MTF (unit 4)	0.4095	2	689	117,655
26268	33061026750000	MTF (unit 4)	0.5726	2	697	92,207
26371	33105031920000	MTF (unit 4)	0.7447	1	698	26,337
26376	33105031960000	MTF (unit 4)	0.6036	2	699	57,305
26382	33061026950000	MTF (unit 4)	0.7208	2	700	53,977
26392	33061026990000	MTF (unit 4)	0.4946	2	693	212,425
26396	33061027030000	MTF (unit 4)	0.5699	2	711	227,912
26405	33105032030000	MTF (unit 4)	0.5572	2	699	117,895
26427	33061027080000	MTF (unit 4)	0.6161	1	690	88,692
26586	33053053230000	MTF (unit 4)	0.6468	1	711	119,492
26615	33053053370000	MTF (unit 4)	0.4743	2	697	165,941
26629	33053053430000	MTF (unit 4)	0.4877	2	705	69,776
26632	33053053460000	MTF (unit 4)	0.5554	3	714	61,951
26721	33025023180000	MTF (unit 4)	0.1863	1	696	279,536
26777	33053053920000	MTF (unit 4)	0.6583	2	693	120,654

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
26832	33053054180000	MTF (unit 4)	0.7683	2	704	44,727
26833	33053054190000	MTF (unit 4)	0.6211	2	697	52,987
26873	33105032920000	MTF (unit 4)	0.7111	2	700	52,112
26875	33105032940000	MTF (unit 4)	0.6640	1	706	62,011
26887	33053054390000	MTF (unit 4)	0.6866	2	704	65,093
26889	33053054410000	MTF (unit 4)	0.6802	2	710	69,154
26990	33053054750000	MTF (unit 4)	0.3275	2	706	465,687
27011	33061028150000	MTF (unit 4)	0.7700	1	694	35,647
27013	33061028170000	MTF (unit 4)	0.8396	1	688	16,197
27112	33053055150000	MTF (unit 4)	0.5684	2	709	107,203
27114	33053055170000	MTF (unit 4)	0.4878	2	705	136,244
27157	33013017560000	MTF (unit 4)	0.7317	2	689	34,635
27221	33061028710000	MTF (unit 4)	0.7458	1	702	34,262
27224	33061028740000	MTF (unit 4)	*b		*LPD	
27337	33061029060000	MTF (unit 4)	0.4546	2	689	121,911
27341	33061029100000	MTF (unit 4)	0.4121	2	703	126,004
27367	33053055750000	MTF (unit 4)	0.4395	1	709	102,329
27451	33025024340000	MTF (unit 4)	0.7421	1	689	109,591
27454	33025024370000	MTF (unit 4)	0.6709	1	695	117,723
27464	33013017640000	MTF (unit 4)	0.7527	1	701	30,544
27499	33061029310000	MTF (unit 4)	0.4462	2	700	142,651
27518	33053056330000	MTF (unit 4)	0.6955	1	707	96,599
27529	33105033940000	MTF (unit 4)	0.5632	2	686	131,262
27541	33053056410000	MTF (unit 4)	0.4188	2	695	128,401
27589	33053056630000	MTF (unit 4)	0.1911	2	694	389,891
27598	33061029460000	MTF (unit 4)	0.7353	1	698	44,379
27601	33061029490000	MTF (unit 4)	0.5584	1	689	100,493
27662	33105034120000	MTF (unit 4)	0.6919	2	706	48,533
27740	33025024700000	MTF (unit 4)	0.2470	1	695	212,880
27760	33053057060000	MTF (unit 4)	0.7581	1	706	80,379
27763	33053057090000	MTF (unit 4)	0.5427	2	689	216,737
27829	33061029970000	MTF (unit 4)	0.4869	2	701	192,162
27906	33061030270000	MTF (unit 4)	0.3447	1	689	220,521
27918	33053057510000	MTF (unit 4)	0.2965	3	695	293,841
27996	33061030330000	MTF (unit 4)	0.6057	2	698	254,672
28015	33053057820000	MTF (unit 4)	0.2945	2	704	366,256
28030	33105034880000	MTF (unit 4)	0.7093	1	691	136,441
28063	33061030530000	MTF (unit 4)	*b		*LPD	
28079	33061030630000	MTF (unit 4)	*b		*LPD	
28127	33105035040000	MTF (unit 4)	0.6470	2	704	48,079
28142	33053058150000	MTF (unit 4)	0.2394	1	714	189,135
28326	33061031030000	MTF (unit 4)	0.2378	1	691	233,771
28379	33053059370000	MTF (unit 4)	0.6833	2	689	86,187
28444	33061031160000	MTF (unit 4)	0.9438	2	*LPD	

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
28480	33061031290000	MTF (unit 4)	0.7054	1	706	50,632
28556	33053059970000	MTF (unit 4)	*b		*LPD	
28558	33053059990000	MTF (unit 4)	*b		*LPD	
28561	33053060010000	MTF (unit 4)	0.5665	2	690	150,278
28565	33053060050000	MTF (unit 4)	0.4281	2	*LPD	
28600	33053060110000	MTF (unit 4)	0.7654	2	699	48,097
28635	33053060200000	MTF (unit 4)	*b		*LPD	
28653	33053060270000	MTF (unit 4)	*b		*LPD	
28654	33053060280000	MTF (unit 4)	0.7407	1	698	71,727
28685	33061031680000	MTF (unit 4)	0.6074	3	686	90,967
28837	33061031890000	MTF (unit 4)	0.5998	2	691	74,669
28846	33061031980000	MTF (unit 4)	0.5505	1	704	146,689
28856	33061032020000	MTF (unit 4)	0.2605	2	711	221,344
28880	33061032090000	MTF (unit 4)	0.5424	1	687	177,951
28923	33061032210000	MTF (unit 4)	0.6165	2	685	173,903
28977	33053061300000	MTF (unit 4)	*b		*LPD	
28982	33025026200000	MTF (unit 4)	0.5207	2	689	266,486
28998	33053061340000	MTF (unit 4)	0.3383	2	696	430,218
29022	33105036470000	MTF (unit 4)	0.5474	1	695	55,092
29048	33053061520000	MTF (unit 4)	0.4645	2	694	115,921
29062	33061032380000	MTF (unit 4)	0.5463	1	703	67,295
29107	33061032490000	MTF (unit 4)	0.4826	1	689	93,942
29151	33061032580000	MTF (unit 4)	0.4958	2	700	78,114
29209	33053062180000	MTF (unit 4)	0.4502	2	692	315,881
29264	33105037150000	MTF (unit 4)	*b		*LPD	
29343	33061032960000	MTF (unit 4)	*b		*LPD	
29347	33061033000000	MTF (unit 4)	*b		*LPD	
29432	33053062820000	MTF (unit 4)	0.4107	2	710	105,088
29433	33053062830000	MTF (unit 4)	0.5827	2	691	94,416
29434	33053062840000	MTF (unit 4)	0.4279	1	704	86,392
29500	33053063110000	MTF (unit 4)	0.6808	2	709	168,830
29554	33025026790000	MTF (unit 4)	0.4089	2	705	254,348
29629	33053063510000	MTF (unit 4)	0.5240	2	693	211,655
29669	33061033510000	MTF (unit 4)	0.2438	1	700	128,512
29671	33061033530000	MTF (unit 4)	0.2963	2	710	325,773
29752	33053063920000	MTF (unit 4)	0.7738	2	701	22,289
29831	33053064170000	MTF (unit 4)	0.4017	3	698	257,906
29932	33053064450000	MTF (unit 4)	0.4497	2	696	401,321
29936	33053064490000	MTF (unit 4)	0.4988	1	690	364,619
29945	33053064500000	MTF (unit 4)	0.4514	1	692	238,995
29949	33053064540000	MTF (unit 4)	0.5526	2	694	209,634
29962	33053064610000	MTF (unit 4)	0.6843	3	712	51,636
29964	33053064630000	MTF (unit 4)	0.6423	2	713	57,459
30048	33053064890000	MTF (unit 4)	0.1806	2	697	214,190

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
30131	33053065180000	MTF (unit 4)	0.7218	3	*LPD	
30136	33025027770000	MTF (unit 4)	0.5668	2	*LPD	
30139	33025027800000	MTF (unit 4)	0.6228	2	*LPD	
30288	33053066050000	MTF (unit 4)	0.6172	2	710	98,250
30335	33053066150000	MTF (unit 4)	0.4520	1	694	248,673
30345	33053066230000	MTF (unit 4)	0.6030	2	700	421,506
30364	33025028040000	MTF (unit 4)	*a		*LPD	
30367	33025028070000	MTF (unit 4)	*a		*LPD	
30404	33053066390000	MTF (unit 4)	0.4355	2	703	307,241
30494	33061035170000	MTF (unit 4)	0.5291	2	690	193,069
30498	33061035210000	MTF (unit 4)	0.5099	2	710	148,969
30524	33061035310000	MTF (unit 4)	0.5865	1	*LPD	
30528	33061035350000	MTF (unit 4)	0.6028	1	*LPD	
30608	33053066940000	MTF (unit 4)	0.4338	2	698	215,453
30647	33061035670000	MTF (unit 4)	0.4281	3	*LPD	
30688	33053067130000	MTF (unit 4)	0.1868	2	703	262,214
30710	33053067180000	MTF (unit 4)	0.8012	2	689	81,367
30775	33053067480000	MTF (unit 4)	*b		*LPD	
30776	33053067490000	MTF (unit 4)	0.2024	1	702	317,316
30906	33053068010000	MTF (unit 4)	0.7327	3	686	148,201
31005	33053068420000	MTF (unit 4)	0.4785	2	700	194,719
31008	33053068450000	MTF (unit 4)	0.5751	1	711	159,245
31029	33061036630000	MTF (unit 4)	0.3177	1	714	104,563
31059	33053068660000	MTF (unit 4)	*b		*LPD	
31147	33053069060000	MTF (unit 4)	0.5537	1	714	96,738
31280	33061036980000	MTF (unit 4)	0.3851	2	705	187,074
31317	33053069700000	MTF (unit 4)	0.3728	2	706	286,181
31319	33053069720000	MTF (unit 4)	0.0584	1	693	214,226
31327	33053069750000	MTF (unit 4)	0.7287	2	697	179,983
31331	33053069790000	MTF (unit 4)	0.7809	2	704	170,316
31397	33053070120000	MTF (unit 4)	0.2357	1	695	185,703
31416	33061037340000	MTF (unit 4)	*b		*LPD	
31422	33061037380000	MTF (unit 4)	0.3918	2	710	221,080
31424	33053070170000	MTF (unit 4)	0.3807	2	696	117,640
31530	33053070690000	MTF (unit 4)	0.5047	2	696	117,640
31576	33053070880000	MTF (unit 4)	0.6307	2	687	140,832
31647	33053071250000	MTF (unit 4)	0.3607	2	699	175,513
31663	33053071360000	MTF (unit 4)	0.3616	1	709	112,440
31665	33053071380000	MTF (unit 4)	0.3073	2	700	130,195
31673	33061037830000	MTF (unit 4)	0.5251	2	689	472,968
31677	33061037870000	MTF (unit 4)	0.6204	2	695	364,618
31693	33053071430000	MTF (unit 4)	0.6540	2	713	179,524
31695	33053071450000	MTF (unit 4)	0.5862	3	689	79,230
31704	33053071480000	MTF (unit 4)	0.3553	2	702	252,848

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
31706	33053071500000	MTF (unit 4)	0.3917	2	686	247,748
31707	33053071510000	MTF (unit 4)	0.3105	1	686	241,637
31711	33053071540000	MTF (unit 4)	0.3572	2	710	270,011
31829	33053072150000	MTF (unit 4)	0.7053	2	689	119,186
31845	33025029930000	MTF (unit 4)	0.5906	1	708	280,957
31849	33061038040000	MTF (unit 4)	0.7791	1	707	124,125
31877	33061038140000	MTF (unit 4)	0.7029	1	695	239,230
31881	33061038180000	MTF (unit 4)	0.5260	2	708	356,711
31962	33025030100000	MTF (unit 4)	*a		*LPD	
31966	33025030140000	MTF (unit 4)	*a		*LPD	
32059	33053072990000	MTF (unit 4)	0.4726	1	697	231,665
32086	33053073160000	MTF (unit 4)	0.4610	2	692	175,837
32107	33053073280000	MTF (unit 4)	0.4378	2	711	200,988
32127	33061038660000	MTF (unit 4)	*a		*LPD	
32131	33061038700000	MTF (unit 4)	*a		*LPD	
32153	33053073400000	MTF (unit 4)	0.4477	2	*LPD	
32217	33025030540000	MTF (unit 4)	0.3341	3	611	289,254
32221	33025030580000	MTF (unit 4)	*c		*LPD	
32305	33053074140000	MTF (unit 4)	*c		*LPD	
32321	33061039070000	MTF (unit 4)	0.3375	1	708	252,507
32323	33061039090000	MTF (unit 4)	0.4388	1	703	193,018
32327	33053074180000	MTF (unit 4)	0.4388	1	703	193,018
32329	33053074200000	MTF (unit 4)	0.2030	1	699	468,538
32344	33053074230000	MTF (unit 4)	0.4931	2	693	182,024
32354	33053074300000	MTF (unit 4)	*a		*LPD	
32356	33053074320000	MTF (unit 4)	0.5235	3	*LPD	
32361	33053074370000	MTF (unit 4)	*b		*LPD	
32362	33053074380000	MTF (unit 4)	*b		*LPD	
32367	33025030880000	MTF (unit 4)	*a		*LPD	
32386	33053074480000	MTF (unit 4)	*b		*LPD	
32387	33053074490000	MTF (unit 4)	*a		*LPD	
32404	33053074540000	MTF (unit 4)	0.8079	3	624	110,402
32454	33053074740000	MTF (unit 4)	0.3914	1	694	386,096
32499	33025031110000	MTF (unit 4)	*a		*LPD	
32501	33025031130000	MTF (unit 4)	*a		*LPD	
32524	33053075060000	MTF (unit 4)	0.5702	2	691	261,683
32576	33053075450000	MTF (unit 4)	0.6515	2	694	262,945
32583	33053075510000	MTF (unit 4)	0.6436	2	702	247,402
32587	33053075550000	MTF (unit 4)	0.4775	2	705	254,498
32606	33061039390000	MTF (unit 4)	0.2966	1	701	502,780
32740	33025031560000	MTF (unit 4)	0.5959	1	710	318,387
32756	33025031640000	MTF (unit 4)	0.6143	3	*LPD	
32806	33025031770000	MTF (unit 4)	0.6841	1	698	247,613
32807	33025031780000	MTF (unit 4)	0.6958	1	693	226,530

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
32816	33025031870000	MTF (unit 4)	*a		*LPD	
32818	33025031890000	MTF (unit 4)	*a		*LPD	
32842	33053076810000	MTF (unit 4)	*a		*LPD	
32890	33053077050000	MTF (unit 4)	0.5536	2	673	335,607
32894	33025032010000	MTF (unit 4)	0.4485	2	*LPD	
33027	33053077880000	MTF (unit 4)	0.4769	3	*LPD	
33100	33053078280000	MTF (unit 4)	*a		*LPD	
33102	33053078300000	MTF (unit 4)	*a		*LPD	
33104	33053078320000	MTF (unit 4)	*a		*LPD	
33109	33053078340000	MTF (unit 4)	*c		*LPD	
33111	33053078360000	MTF (unit 4)	0.6006	3	*LPD	
33114	33053078390000	MTF (unit 4)	*a		*LPD	
33116	33053078410000	MTF (unit 4)	*a		*LPD	
33122	33025032380000	MTF (unit 4)	0.6492	1	*LPD	
33150	33053078560000	MTF (unit 4)	0.2963	2	649	489,068
33222	33053078750000	MTF (unit 4)	*a		*LPD	
33226	33053078790000	MTF (unit 4)	0.6943	1	*LPD	
33231	33053078840000	MTF (unit 4)	*a		*LPD	
33268	33053079120000	MTF (unit 4)	0.4733	1	696	151,499
33273	33061040000000	MTF (unit 4)	0.6208	2	705	176,835
33332	33053079450000	MTF (unit 4)	0.4848	1	715	122,323
33412	33053079550000	MTF (unit 4)	0.3147	1	*LPD	
33416	33053079590000	MTF (unit 4)	0.3646	1	705	345,092
33462	33053079650000	MTF (unit 4)	0.5126	3	*LPD	
33477	33053079770000	MTF (unit 4)	0.4687	1	697	161,792
33479	33053079790000	MTF (unit 4)	0.4812	2	692	135,679
33494	33053079910000	MTF (unit 4)	0.3794	2	706	417,597
33539	33053080030000	MTF (unit 4)	*a		*LPD	
33558	33025032990000	MTF (unit 4)	0.6470	2	703	312,516
33643	33053080520000	MTF (unit 4)	*a		*LPD	
33649	33053080570000	MTF (unit 4)	*a		*LPD	
33700	33053080690000	MTF (unit 4)	*c		551	333,803
33723	33053080720000	MTF (unit 4)	0.3177	1	708	292,752
33724	33053080730000	MTF (unit 4)	0.4279	1	714	97,591
33728	33053080770000	MTF (unit 4)	*a		*LPD	
33729	33061040820000	MTF (unit 4)	*a		*LPD	
33731	33061040840000	MTF (unit 4)	*a		*LPD	
33812	33053080920000	MTF (unit 4)	0.2507	1	661	319,418
33905	33053081220000	MTF (unit 4)	*a		*LPD	
33906	33053081230000	MTF (unit 4)	*a		*LPD	
33914	33053081310000	MTF (unit 4)	*a		*LPD	
33929	33053081390000	MTF (unit 4)	*a		*LPD	
33930	33053081400000	MTF (unit 4)	*a		*LPD	
33965	33053081520000	MTF (unit 4)	0.3962	2	*LPD	

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
33982	33053081600000	MTF (unit 4)	0.5573	2	564	420,623
34007	33053081730000	MTF (unit 4)	0.4573	3	*LPD	
34100	33053082230000	MTF (unit 4)	*c		*LPD	
34103	33053082260000	MTF (unit 4)	0.3878	2	580	478,381
34157	33025033800000	MTF (unit 4)	*b		*LPD	
34161	33025033840000	MTF (unit 4)	*b		*LPD	
34173	33053082390000	MTF (unit 4)	*a		*LPD	
34176	33053082420000	MTF (unit 4)	0.5666	3	*LPD	
34180	33053082460000	MTF (unit 4)	0.6174	2	*LPD	
34193	33053082510000	MTF (unit 4)	0.4543	1	*LPD	
34196	33053082540000	MTF (unit 4)	0.4688	3	*LPD	
34197	33053082550000	MTF (unit 4)	*a		*LPD	
34200	33053082580000	MTF (unit 4)	*a		*LPD	
34352	33025034010000	MTF (unit 4)	0.4529	3	*LPD	
35081	33025035170000	MTF (unit 4)	0.2863	2	*LPD	
35109	33025035250000	MTF (unit 4)	*a		*LPD	
35273	33025035620000	MTF (unit 4)	0.3117	2	*LPD	
35963	33053089160000	MTF (unit 4)	*a		*LPD	
36221	33053089820000	MTF (unit 4)	*b		*LPD	
36720	33053091440000	MTF (unit 4)	*b		*LPD	
36723	33053091470000	MTF (unit 4)	*b		*LPD	
36732	33053091520000	MTF (unit 4)	*b		*LPD	
36913	33053091960000	MTF (unit 4)	*a		*LPD	
37286	33053093270000	MTF (unit 4)	*b		*LPD	
24225	33025019550000	LTF (unit 2)	0.3129	2	705	157,623
24284	33025019670000	LTF (unit 2)	*c		688	126,461
24350	33025019860000	LTF (unit 2)	0.2918	2	709	131,435
24377	33105028910000	LTF (unit 2)	0.6077	2	712	88,363
24431	33025020030000	LTF (unit 2)	0.2281	1	704	204,558
24493	33105029200000	LTF (unit 2)	0.7002	2	711	66,209
24593	33023009640000	LTF (unit 2)	0.7334	1	704	49,403
24806	33053047320000	LTF (unit 2)	0.8808	3	700	15,157
24814	33053047390000	LTF (unit 2)	0.5920	3	709	96,835
24838	33053047450000	LTF (unit 2)	*b		*LPD	
24844	33053047490000	LTF (unit 2)	0.8476	2	619	23,090
24929	33023009980000	LTF (unit 2)	0.7429	2	686	35,920
24934	33023010010000	LTF (unit 2)	0.7280	1	698	28,957
24935	33023010020000	LTF (unit 2)	0.7547	1	695	32,284
25688	33061025820000	LTF (unit 2)	0.5502	1	693	161,096
26588	33053053240000	LTF (unit 2)	0.7552	2	699	66,704
26627	33053053420000	LTF (unit 2)	0.5457	3	688	35,058
26631	33053053450000	LTF (unit 2)	*c		693	20,268
26769	33053053910000	LTF (unit 2)	0.7005	3	688	99,235
26781	33061027730000	LTF (unit 2)	0.5923	2	702	78,945

Table 1. continued

NDIC Well #	API Well Number	Stratigraphic Unit	Water-Cut (fraction)	Water-Cut Quality Code	Production Days	Cumulative Oil (BBLS)
26877	33105032960000	LTF (unit 2)	*d		685	42,762
27109	33053055120000	LTF (unit 2)	0.6480	3	698	51,851
27453	33025024360000	LTF (unit 2)	*b		*LPD	
27455	33025024380000	LTF (unit 2)	0.6247	2	690	154,605
27761	33053057070000	LTF (unit 2)	0.8118	3	*LPD	
27827	33061029950000	LTF (unit 2)	0.6502	2	713	158,799
27831	33061029990000	LTF (unit 2)	0.6140	3	711	80,624
27907	33061030280000	LTF (unit 2)	0.5972	1	708	112,827
27976	33053057720000	LTF (unit 2)	0.8245	3	*LPD	
28002	33061030390000	LTF (unit 2)	0.5642	1	711	337,921
28061	33061030510000	LTF (unit 2)	0.4691	2	700	256,872
28668	33061031620000	LTF (unit 2)	0.4226	2	703	165,480
28845	33061031970000	LTF (unit 2)	0.7024	1	687	76,075
28854	33061032000000	LTF (unit 2)	0.4434	1	691	145,497
29322	33061032940000	LTF (unit 2)	*c		697	79,554
30609	33053066950000	LTF (unit 2)	*d		712	222,171
31533	33053070720000	LTF (unit 2)	0.4784	1	688	77,153
32083	33053073130000	LTF (unit 2)	*c		698	158,936
32343	33053074220000	LTF (unit 2)	0.6142	2	711	132,969
32345	33053074240000	LTF (unit 2)	0.6626	2	695	153,303
33547	33053080390000	LTF (unit 2)	0.5848	1	685	157,282

1 = low variability in water cut (less than +/- 5%)
2 = moderate variability in water-cut (+/- ~10%)
3 = limited number of production days and/or highly variable water cut

*a = completed and active well (or inactive <6 months) with <540 days of production
*b = uncompleted, temporarily abandoned, inactive (>6 months), and/or plugged and abadoned with minimal to no production
*c = Unreliable, variable water-cut
*d = water-cut steadily increases
*LPD = Limited (<700 days) to negligible production days

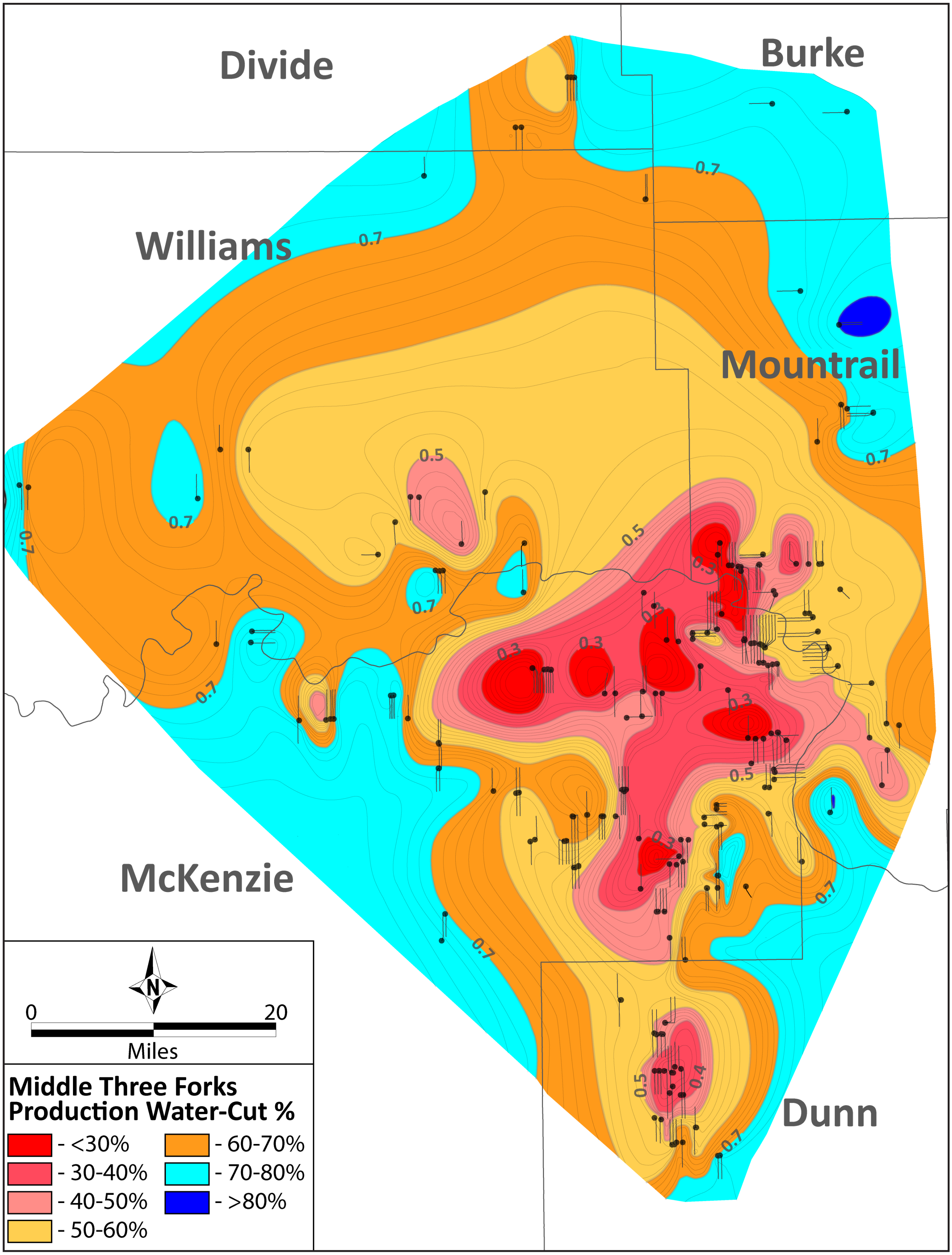


Figure 4. Contour map depicting calculated middle Three Forks water-cut from horizontal well production. Water-cut contours are in 0.01 fractional increments. Black dots and lines represent surface locations and corresponding horizontal boreholes for middle Three Forks wells used to create the water-cut map.

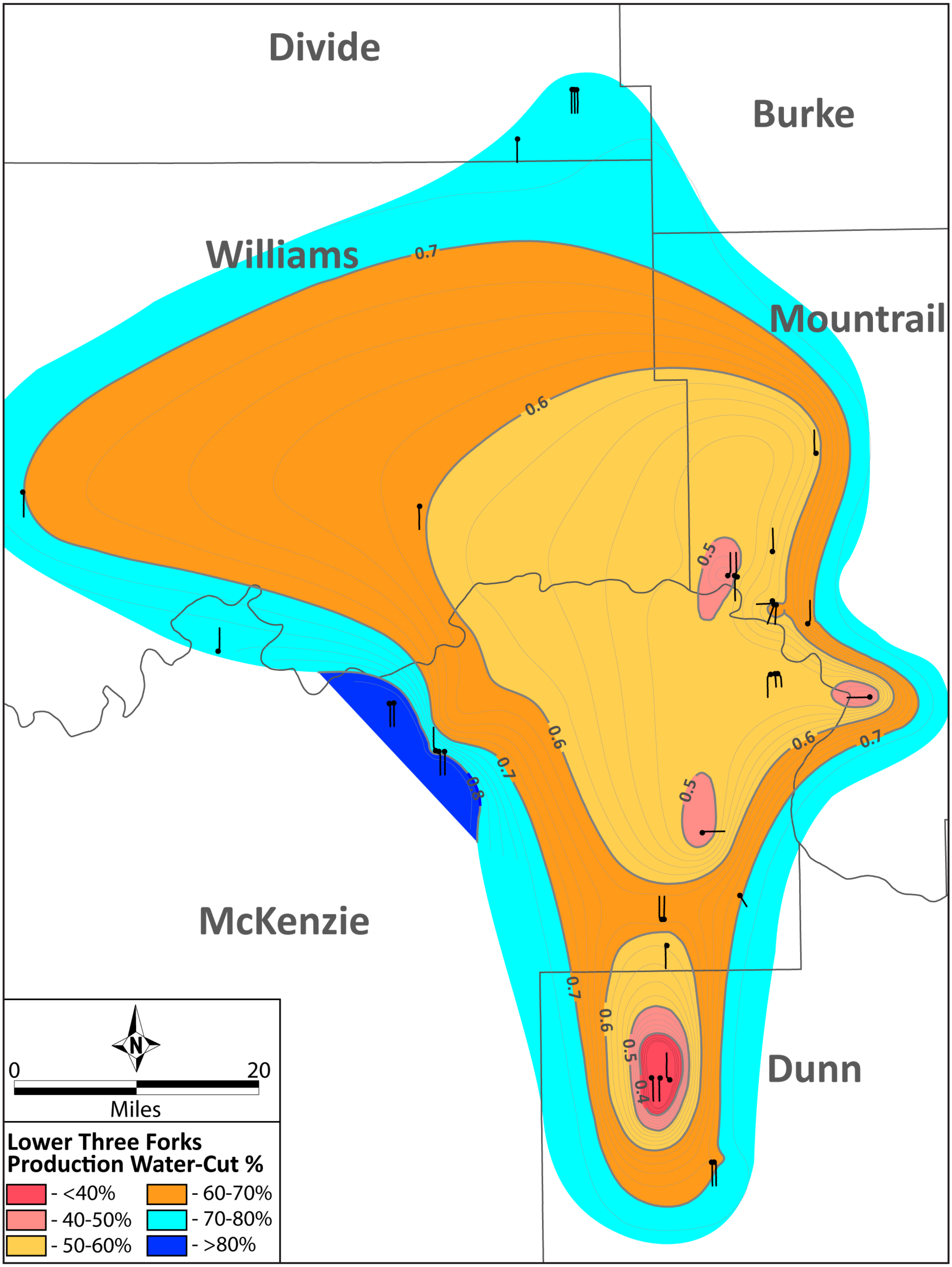


Figure 5. Contour map depicting calculated lower Three Forks water-cut from horizontal well production. Water-cut contours are in 0.01 fractional increments. Black dots and lines represent surface locations and corresponding horizontal boreholes for lower Three Forks wells used to create the water-cut map.

Calculated average water-cut values by well ranged from 23% to 82% with an average of 61%. Only two relatively small multi-well clusters exhibit water-cut's below 50%, with two additional single-well defined areas (Fig. 5). A relatively large and seemingly continuous area of intermediate, 50-70% water-cut for the lower Three Forks extends throughout the central portions of the study area (Fig. 5). However, the number and distribution of lower Three Forks horizontal wells is much more limited than the middle Three Forks. Water-cut increases to above 70% for multiple wells towards the north and southwest, and overall increases moving out radially from the central portions of the study area (Fig. 5).

INTERPRETATIONS AND DISCUSSION

Middle Three Forks Water-Cut versus Core-Plug Oil Saturations

Comparing the middle Three Forks water-cut map (Fig. 4) with a previously published core-plug fluid saturation overlay, the water-cut from productive wells trends spatially with core-plug fluid saturations for the middle Three Forks. Nesheim (2018; 2019) utilized core-plug fluid saturation data to subdivide the middle Three Forks into three areas based upon average oil and water saturations. Figure 6a overlays the middle Three Forks core-plug fluid saturation areas from Nesheim (2019) with the water-cut map for the unit in which the highest core-plug oil (So) and lowest core-plug water (Sw) saturation area (>30% average So, <50% average Sw) spatially overlies with most of the sub-50% water-cut area. Additionally, the intermediate fluid saturation area (10-30% average So, 50-70% average Sw) corresponds with approximately the intermediate, 50-70% water-cut area while the highest water-cut and core-plug water saturation areas also trend closely together along the outer portions of the study area (Fig. 6a). The core-plug fluid saturations and production water-cut trends are not exact matches, likely in part to the varying amount of well/core control for each data set. Also, core-plug fluid saturation rarely represents ~100% of the original fluids because of the leaking/evaporation of formational fluids upon the initial extraction of the core from the subsurface as well as variations in post-extraction handling and analysis of the rock. However, these spatial relationships demonstrate that core-plug fluid saturation data can be used to variable degrees as a proxy for producible fluid ratios.

Middle Three Forks Water-Cut versus Lower Bakken Thickness and Thermal Maturity

Similar to core-plug oil saturations, middle Three Forks water-cut can also be directly linked to thickness and thermal maturity trends in the Lower Bakken. Elevated core-plug oil saturations in the middle Three Forks have been previously correlated with increased thickness and thermal maturity of the Lower Bakken (Nesheim, 2019). Likewise, the central, low water-cut area (<50%) of middle Three Forks production is largely positioned within the area of thicker (>20 ft.) and most thermally mature (HI: <200) Lower Bakken (Fig. 6b). Additionally, most of the intermediate middle Three Forks water-cut area (50-70%) overlaps with where the Lower Bakken is still relatively thick (>20 ft.) but at intermediate levels of thermal maturity (HI: 200-400), and the highest water-cut areas mostly correlate with where the Lower Bakken is thinner (<20 ft.) and/or less thermally mature (HI: >400) (Fig. 6b). The increase in thickness and thermal maturity for the Lower Bakken corresponds with greater volumes of hydrocarbons being generated and expelled into the underlying Three Forks, which in turn displaces more of the natural formation water and decreases the amount of free water in the system. Conversely, as the Lower Bakken decreases in thickness and/or thermal maturity, lower volumes of hydrocarbons are generated and expelled into the Three Forks and less of the natural formation waters are displaced.

Middle Three Forks Water-Cut versus Well Performance

For a preliminary evaluation of middle Three Forks well performances versus water-cut, 700-day cumulative oil production totals were tabulated (Fig. 6c and Table 1). Initial production (IP) rates are commonly reported by industry and utilized to varying degrees to compare well production results. However, IP reporting systems can vary between operators where some IP's reflect 2-hour flow tests that are extrapolated up to a 24-hour period versus multi-day flow tests that are averaged down to a 24-hour flow rate (typically yields lower, more conservative IP's) as well as a variety of other variations (e.g., choking back initial production). Also, unconventional wells commonly experience steep declines in production rates for the first several months following initial completions, after which production rates may stabilize. Therefore, 700-day cumulative oil production totals were utilized to standardize the comparison of oil well production performances. Seven-hundred-day cumulative oil production totals for middle Three Forks wells ranged from approximately 16,000 barrels of oil to upwards of 503,000 barrels of oil with an average of 174,000 barrels (Fig. 6c and Table 1). Most of the higher 700-day oil producers (200,000-300,000+ barrels of oil) are located within or next to the area of sub-50% water-cut while the majority of lowest producers (<50,000 barrels of oil) plot within or are proximal to the >70% water-cut areas (Fig. 6c). Overall, 700-day cumulative oil production totals for middle Three Forks wells share an inverse relationship to water-cut where increased oil production corresponds to decreased water-cut.

Middle Three Forks Water-Cut versus Structure

A substantial number of middle Three Forks wells are located either along or proximal to the Nesson and Antelope anticlines. Natural fracture systems can occur along structures which may bolster reservoir performance. While some of the middle Three Forks wells may benefit from structurally related natural fracture systems (e.g. northwestern Dunn County – Fig. 6c and 6d), there are dozens of productive middle Three Forks wells with low water-cut and/or high 700-day oil cumulative production totals that are not proximal to documented, published Williston Basin structures (e.g. south-central Williams and southwestern Mountrail Counties – Fig. 6c and 6d). However, undocumented structures likely exist in portions of the basin.

Lower Three Forks Water-Cut versus Various Factors

The lower Three Forks water-cuts share similar spatial relationships to increased core-plug saturations, Lower Bakken thickness-thermal maturity, structural features, and 700-day cumulative oil production totals as described above for the middle Three Forks (Fig. 7a-d). The lower Three Forks core-plug oil saturations from Nesheim (2019) never reach the same elevated averages (>30% So) as the overlying middle Three Forks, and likewise the lower Three Forks water-cut does not decrease below 50%, but increased core-plug oil saturations correlate overall with decreased water-cut for the unit (Fig. 7a). Most of the low water-cut area for lower Three Forks production (<60% water-cut) corresponds to the area of thicker, more thermally mature Lower Bakken while decreased thickness and/or thermal maturity correlates with higher water-cuts (Fig. 7b). Seven-hundred-day cumulative oil production totals for the lower Three Forks wells ranged from approximately 15,000 to 338,000 barrels with an average of around 110,000 barrels (Table 1). Most of the more productive wells (700-day cum. oil: 200,000-300,000+ barrels) are located within or next to the area of sub-60% water-cut while the majority of lower producers (<50,000-100,000 barrels of oil) plot within or proximal to the >70% water-cut areas (Fig. 7c). Some of the productive horizontal lower Three Forks wells are positioned along documented structures while other are positioned away from known structures (Fig. 7d).

ADDITIONAL DISCUSSION NOTES

Several factors may influence water-cut either in the short-term or long-term for a given oil well. Water-cut will naturally increase over the life of some wells as continued production depletes oil from a reservoir. Multiple middle and lower Three Forks horizontal wells were observed to show slight increases in water-cut over the first several years of production (e.g. Fig. 3a), while other well's displayed slight decreases in water-cut or remained flat during production to date. In addition, water flooding (injection) for enhanced oil recovery (EOR) efforts can artificially increase a reservoirs water-cut indefinitely until after the water flooding efforts are ceased. However, while a few small-scale water flooding projects have been attempted within the Bakken-Three Forks play of North Dakota, it has yet to become an effective, continued practice within the state.

Hydraulic fracturing is another prominent influence on artificially altering the water-cuts of middle and lower Three Forks horizontal wells. The present-day standard completion of horizontal Three Forks wells involves injecting large volumes of water-based fluid into the reservoir during the process of multi-stage hydraulic fracturing. The injected water-based fluid artificially increases the reservoir's oil-water ratio proximal to the completed well's borehole and thereby temporarily increases the well's early water production rates along with water-cuts. Most injected water-based fluid is typically recovered during the first several months of production, which is why the first 6-12 months of production for each well were generally excluded for calculating the water-cut. The amount of injected water varies from one unconventional well to another and the rate of producing the injected water will also vary. Hydraulic fracturing of proximal wells during either initial completions and/or re-stimulations can also temporarily influence the water-cut of select wells, which may be one prominent reason that the water-cut of some evaluated wells did not stabilize for the first 1-2+ years of production. Interestingly, a handful of middle to lower Three Forks horizontal wells displayed a slight to moderate increase in water-cut during the initial several months following the initial hydraulic fracture completions (e.g. Fig. 3a).

Finally, the induced fracture system created during the multi-stage hydraulic fracturing process may not always be limited to the targeted stratigraphic interval. Induced fractures held open by injected proppant extend outwards in all directions from a given stimulated horizontal borehole. The induced open fractures may extend into over- and/or underlying stratigraphic intervals which may increase or decrease the water-cut of a given hydraulically fractured horizontal well.

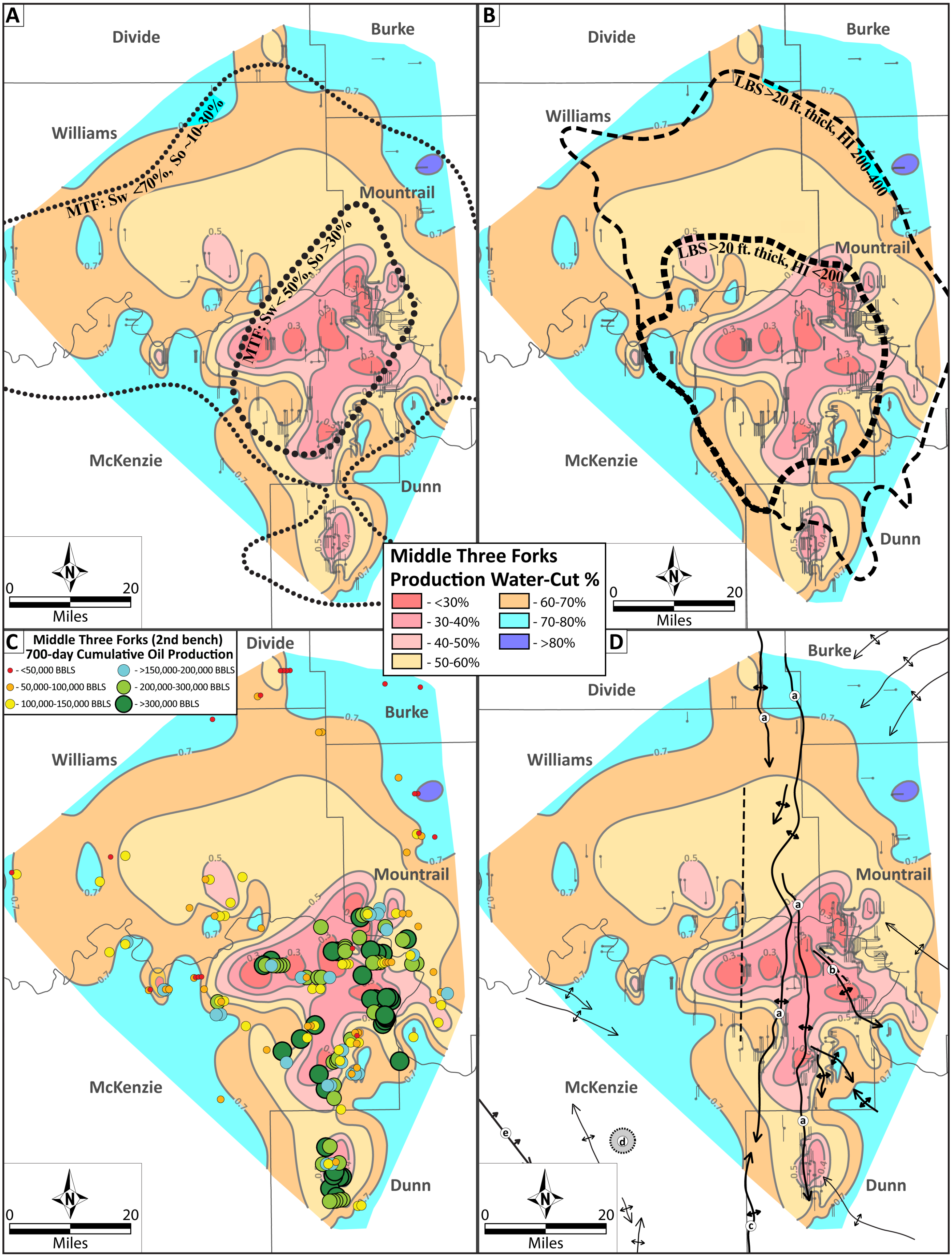


Figure 6. Middle Three Forks (MTF) water-cut contour map (color-fill and gray lines) overlain by A) MTF core-plug fluid saturation information (Nesheim, 2019), B) lower Bakken areas of similar thickness (feet) and thermal maturity (HI = hydrogen index) (Nesheim, 2019), C) MTF 700-day cumulative oil production bubbles, and D) Williston Basin structural features. a = Nesson anticline; b = Antelope anticline; c = Little Knife anticline; d = Red Wing Creek structure; e = Mondak monocline

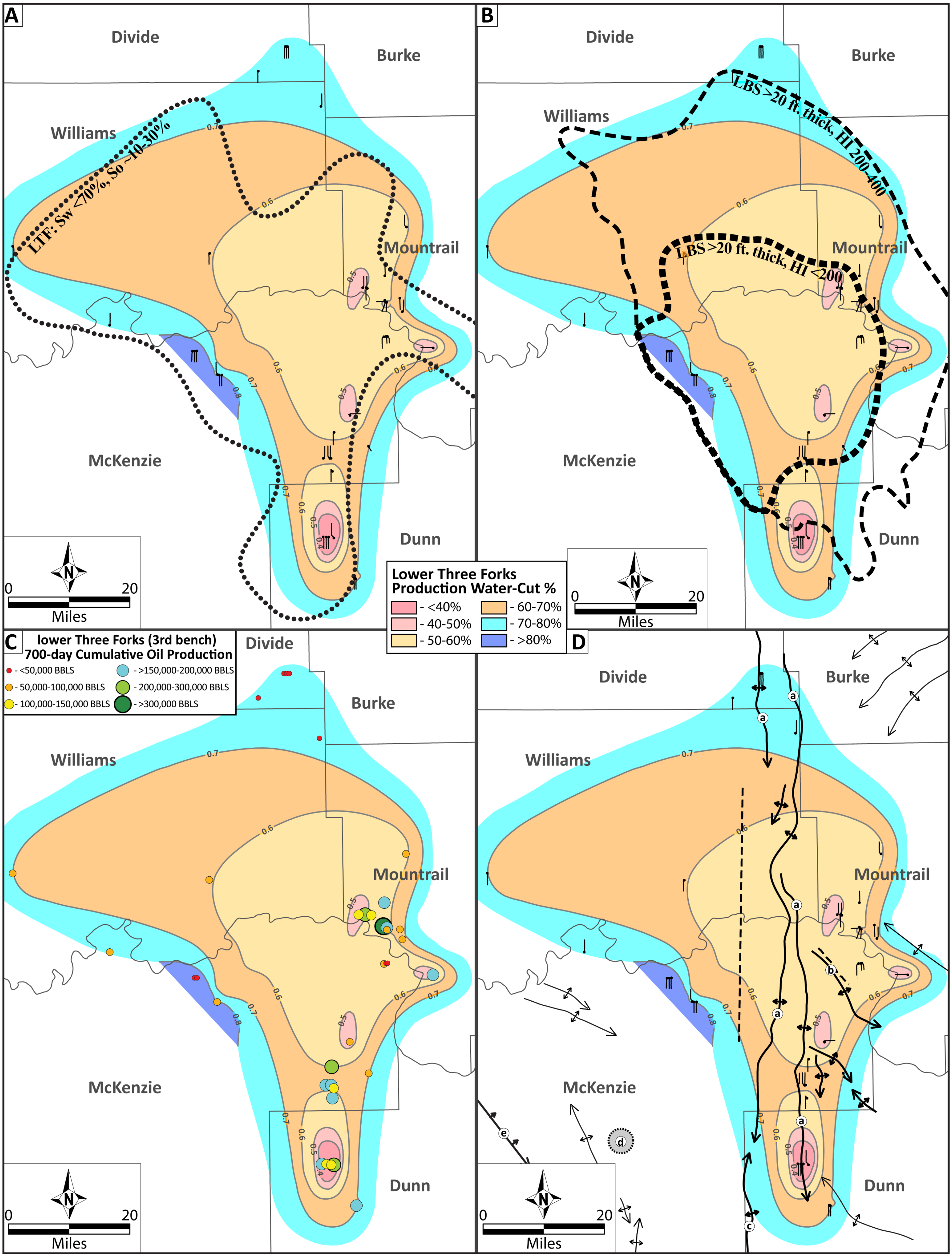


Figure 7. Lower Three Forks (LTF) water-cut contour map (color-fill and gray lines) overlain by A) LTF core-plug fluid saturation information (Nesheim, 2019), B) Lower Bakken areas of similar thickness (feet) and thermal maturity (HI = hydrogen index) (Nesheim, 2019), C) LTF 700-day cumulative oil production bubbles, and D) Williston Basin structural features. a = Nesson anticline; b = Antelope anticline; c = Little Knife anticline; d = Red Wing Creek structure; e = Mondak monocline

References:

Bottjer, R.J., Sterling, R., Grau, A., Dea, P., 2011. Stratigraphic relationships and reservoir quality at the three forks-Bakken unconformity, Williston Basin, North Dakota. In: Robinson, L., LeFever, J., Gaswirth, S. (Eds.), Bakken-Three Forks Petroleum System in the Williston Basin: Rocky Mountain Association of Geologists Guidebook, pp. 173–228.

Christopher, J. E., 1961, Transitional Devonian-Mississippian Formation of Southern Saskatchewan. Regina, Saskatchewan, Canada, Saskatchewan Mineral Resources Geological Report 66, pp. 103.

Christopher, J. E., 1963, Lithological and geochemical aspects of the Upper Devonian Torquay Formation, Saskatchewan: Journal of Sedimentary Petrology, v. 33, pp. 5–13.

Nesheim, T.O., 2018, Examination of Oil Saturations and Horizontal Well Production for the Middle and Lower Three Forks Formation: North Dakota Geological Survey, Geological Investigations No. 205, 23 pp.

Nesheim, T.O., 2019, Examination of downward hydrocarbon charge within the Bakken-Three Forks petroleum system – Williston Basin, North America: Marine and Petroleum Geology, v. 104, p. 346-360.

Nesheim, T.O., 2020a, History of Exploration and Development in the Middle Three Forks (2nd Bench): North Dakota Department of Mineral Resources, Geo Newsletter, vol. 47, no. 2, p. 18-20.

Nesheim, T.O., 2020b, Preliminary Middle and Lower Three Forks (2nd bench) Horizontal Well Identification: North Dakota Geological Survey, Geological Investigations No. 244, 8 pp.

Nesheim, T.O., 2021, Overview of Development History and Future Potential for the lower Three Forks Formation (3rd bench): Bakken-Three Forks Petroleum System: North Dakota Department of Mineral Resources, Geo Newsletter, vol. 48, no. 1, p. 24 - 28.