Interpreting the past, providing for the future

Codell Sandstone Oil Production Trends, Northern Denver Basin, Laramie County, Wyoming

By Rachel N. Toner and Erin A. Campbell

Open File Report 2017-2
May 2017

Wyoming State Geological Survey

Thomas A. Drean, Director and State Geologist

Codell Sandstone Oil Production Trends, Northern Denver Basin, Laramie County, Wyoming

By Rachel N. Toner and Erin A. Campbell

Layout by Christina D. George

Open File Report 2017-2
Wyoming State Geological Survey
Laramie, Wyoming: 2017

This Wyoming State Geological Survey (WSGS) Open File Report is preliminary and may require additional compilation and analysis. Additional data and review may be provided in subsequent years. For more information about the WSGS, or to download a copy of this Open File Report, visit www.wsgs.wyo.gov. The WSGS welcomes any comments and suggestions on this research. Please contact the WSGS at 307-766-2286, or email wsgs-info@wyo.gov.

Citation: Toner, R.N., and Campbell, E.A., 2017, Codell Sandstone oil production trends, Northern Denver Basin, Laramie County, Wyoming: Wyoming State Geological Survey Open File Report 2017-2, 40 p.

Table of Contents

List of Figures

List of Tables

ABSTRACT

The oil-bearing Codell Sandstone was historically deemed uneconomical due to its low porosity and permeability, and its lack of traditional hydrocarbon trap. With recent advances in horizontal drilling and hydraulic fracturing (frac) methods, this unconventional tight sand is now proving to be a highly productive oil reservoir. This study investigates the characteristics of the highest-producing Codell Sandstone wells in Laramie County, Wyoming. Identifying operational best practices can aid industry and regulators in optimizing future oil production from the Codell Sandstone in the northern Denver Basin.

The initial, first-months, and cumulative production of all horizontal wells producing from the Codell Sandstone in Laramie County, Wyoming, were compared spatially to isopach and structure contour maps. Production was also cross-plotted against drilling and completion practices utilized in this area, specifically lateral length, lateral orientation, and completion techniques. These spatial and graphical comparisons indicate that while thickness and formation depth do not appear to influence well production, wells with long laterals oriented north-south have consistently superior production than those drilled with shorter lengths and alternate directions. The optimum number of frac stages and amounts of slurry and proppant currently used to complete Codell Sandstone wells are also assessed.

INTRODUCTION

Scope of report

Unconventional reservoirs have become a primary source of new oil production in Wyoming. While traditional oil and gas reservoirs are typically thick, porous, and permeable sandstones and carbonates with underlying source rocks and defined traps and pools, unconventional reservoirs are "tight" sands and shales where the oil is distributed throughout pore spaces. Advanced horizontal drilling and completion techniques, along with thorough petrophysical and geomechanical reservoir analyses, are vital in developing these low porosity and permeability formations.

The Codell Sandstone Member of the Upper Cretaceous Carlile Shale in the Denver Basin of Wyoming (hereafter referred to as the northern Denver Basin) is an unconventional reservoir that is emerging as a notable oil producer because of these techniques. Significant recent production from this thin, tight sandstone in the northern Denver Basin surprised operators who had been focusing their efforts on reproducing the successful Niobrara Formation production seen in Colorado. As production is ultimately the best indicator of a well's success or failure, this report compares oil production and conventional geologic analysis, such as identifying reservoir thickness and structure, to demonstrate that for the Codell Sandstone, traditional geologic criteria do not predict successful production. Instead, production best correlates with lateral direction, lateral length, and completion techniques.

Geologic setting

The Denver Basin is a relatively deep, asymmetrical, Laramide-age foreland basin spanning southeastern Wyoming, northeastern Colorado, and southwestern Nebraska. In Wyoming, the basin is bounded on the west by the Laramie Mountains and on the north by the Hartville uplift (fig. 1). The Denver Basin axis is located closer to the western edge of the basin and reaches a maximum depth of approximately 13,000 ft (Sonnenberg, 1987). The axis parallels the Precambrian uplifts to the west and generally trends north-south except in the northernmost part of the basin, where it is oriented northeast-southwest. Strata on the west side of the basin dip more steeply than those east of the axis. Cretaceous-age formations make up the thickest portion of the Denver Basin's geologic section, but are seldom exposed at the surface. Most outcrops in the Wyoming portion of the basin are Paleogene in age.

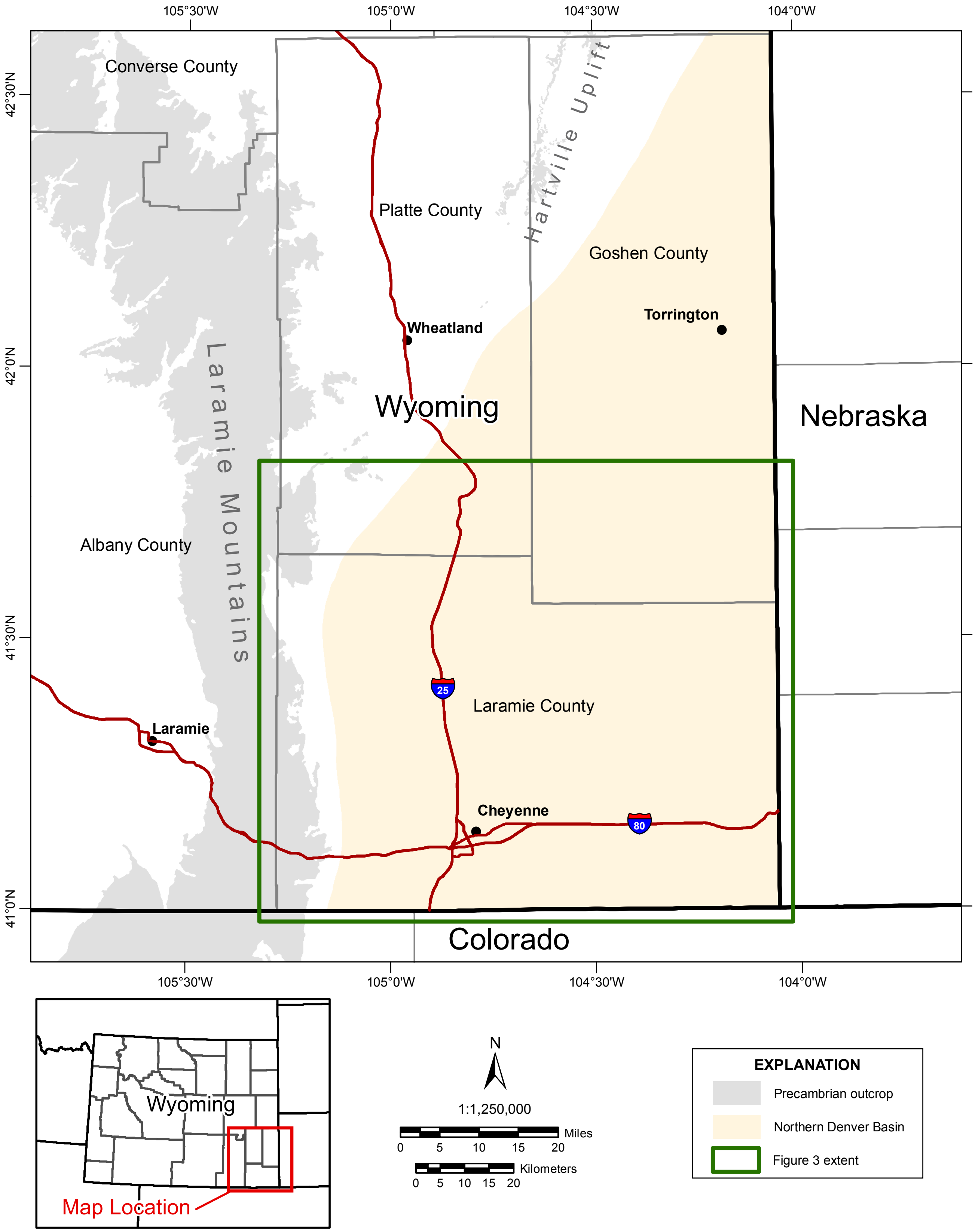


Figure 1. Overview map of the northern Denver Basin in southeastern Wyoming. Precambrian outcrops uplifted during the Laramide orogeny flank the basin on the north and west. The green rectangle indicates the area shown in figure 3.

Codell Sandstone

The Codell Sandstone was deposited during the Turonian in an alternating deltaic, intertidal, and shallow marine shelf environment along the eastern margin of the Cretaceous seaway (Sonnenberg, 2014; Anderson, 2011; Krutak, 1970). The sediment source is somewhat unclear, as some suggest a western thrust belt origin (Sonnenberg, 2014; Anderson, 2011), while Sterling and others (2016) propose sediment input from the eastern craton. Anderson (2011) shows the Sage Breaks Member of the Carlile Shale unconformably overlying the Codell Sandstone in much of the study area, but Sterling and others (2016) suggest that the Sage Breaks pinches out to the south, with the Fort Hayes Limestone of the Niobrara Formation forming the Codell's upper unconformable contact. The base of the Codell is defined by an unconformable contact with the lower shale member of the Carlile Shale.

The Codell Sandstone is a relatively thin sandstone, averaging 20–30 ft throughout most of the basin. Although Anderson (2011) indicates a maximum thickness of 100 ft in the far northwest portion of the basin, others (Sterling and others, 2016) suggest that the Codell is often confused for a Frontier Formation member in the northernmost portion of the basin and actually pinches out altogether in Goshen County, Wyoming. In the southern Colorado portion of the Denver Basin, the Codell also thins considerably due to erosion and deposition of the overlying Fort Hayes Limestone Member of the Niobrara Formation. Cross-sections generated by Anderson (2011) confirm that the Codell Sandstone does not branch into stacked thinner layers, but instead remains integrated and coherent throughout the study area (fig. 2).

In the study area, the Codell Sandstone is described as a fine-grained, well-sorted, quartz sandstone with up to 20 percent clay and up to 20 percent feldspar, with significant carbonate cementation near the top and base (Sterling and others, 2016; Anderson, 2011). Planar to hummocky cross-bedded sedimentary structures, bioturbated and laminated facies, and abundant mud drapes are observed (Sterling and others, 2016; Anderson, 2011; Weimer and Sonnenberg, 1983). Cores from the Codell Sandstone have yielded porosity measurements generally ranging from 8 to 17 percent (Sterling and others, 2016; Anderson, 2011) and permeability less than 1 millidarcy (md; Anderson, 2011) but typically less than 0.01 md (Sterling and others, 2016).

Oil produced from the Codell Sandstone was sourced and migrated from surrounding formations. Multiple authors indicate the Graneros Shale, Greenhorn Formation, and lower member of the Carlile Shale as likely source rocks within the Denver Basin (Sonnenberg, 2014; Anderson, 2011; Rice and Threlkeld, 1983; Clayton and Swetland, 1980;). Others also propose that the Niobrara Formation is a probable source of oil in the Codell Sandstone (Sterling and others, 2016; Birmingham and others, 2001; Weimer and Sonnenberg, 1983). Sterling and others (2016) suggest that oil migration into the Codell could be facilitated in areas where the Niobrara's lower C Marl zone directly overlies the Fort Hays Limestone, and oil was able to move along fractures in the Fort Hays into the lower-pressure Codell Sandstone. Gas-to-oil ratios (GOR) recorded on Wyoming Oil and Gas Conservation Commission (WOGCC) completion reports for the horizontal wells included in this study average 594; oil averages 37.1 API gravity. In the Colorado portion of the Denver Basin near the Wattenberg field, Sonnenberg (2015) reports GORs in the Codell as high as 40,000 due to significantly higher geothermal gradients.

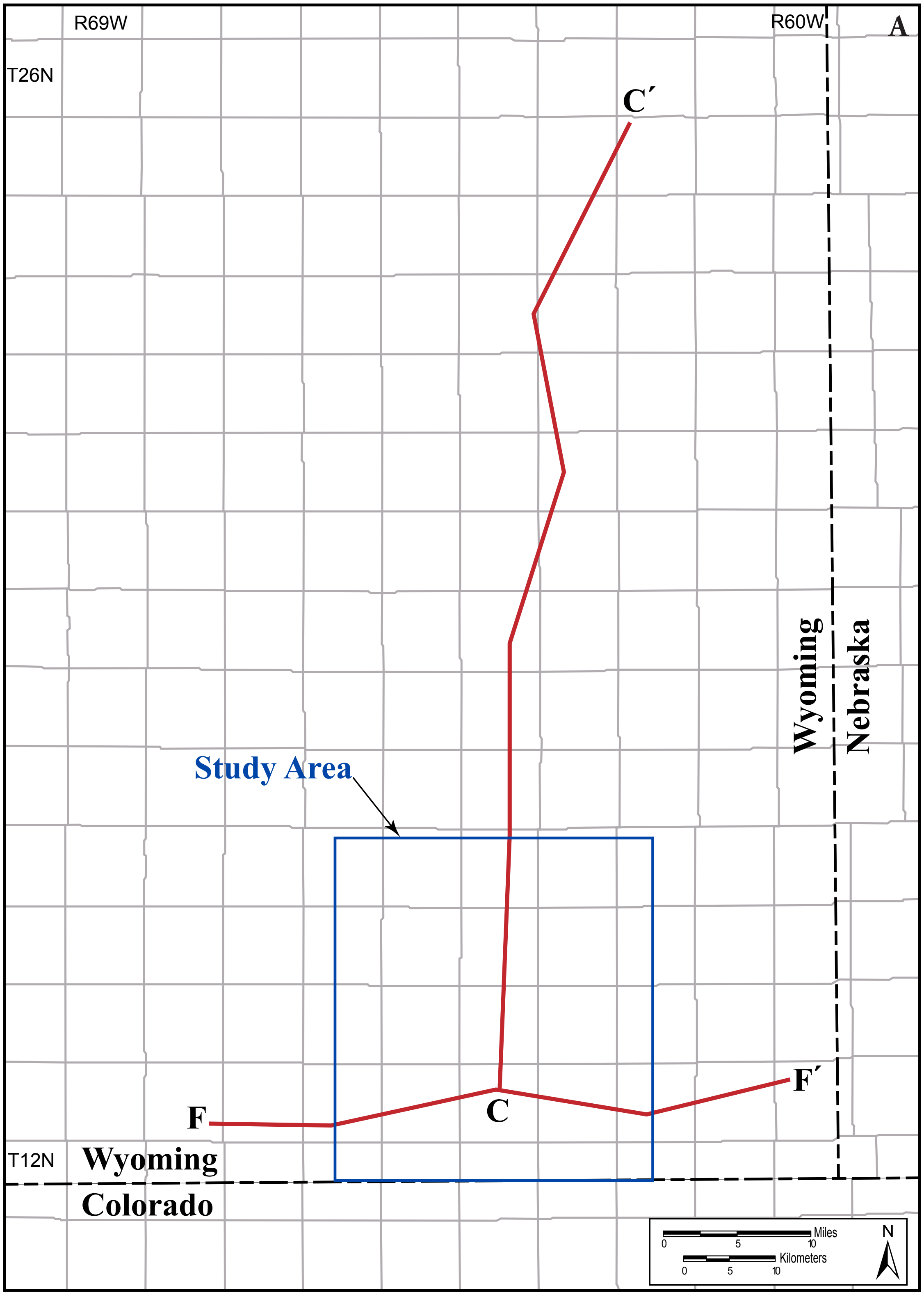


Figure 2. Cross sections based on correlations of vertical wells in the northern Denver Basin, modified from Anderson (2011). The map (A) shows the location of the two cross section lines, oriented (B) north-south and (C) east-west. These lines extend beyond the study area of this report, but are included to show the lateral consistency of the Codell Sandstone.

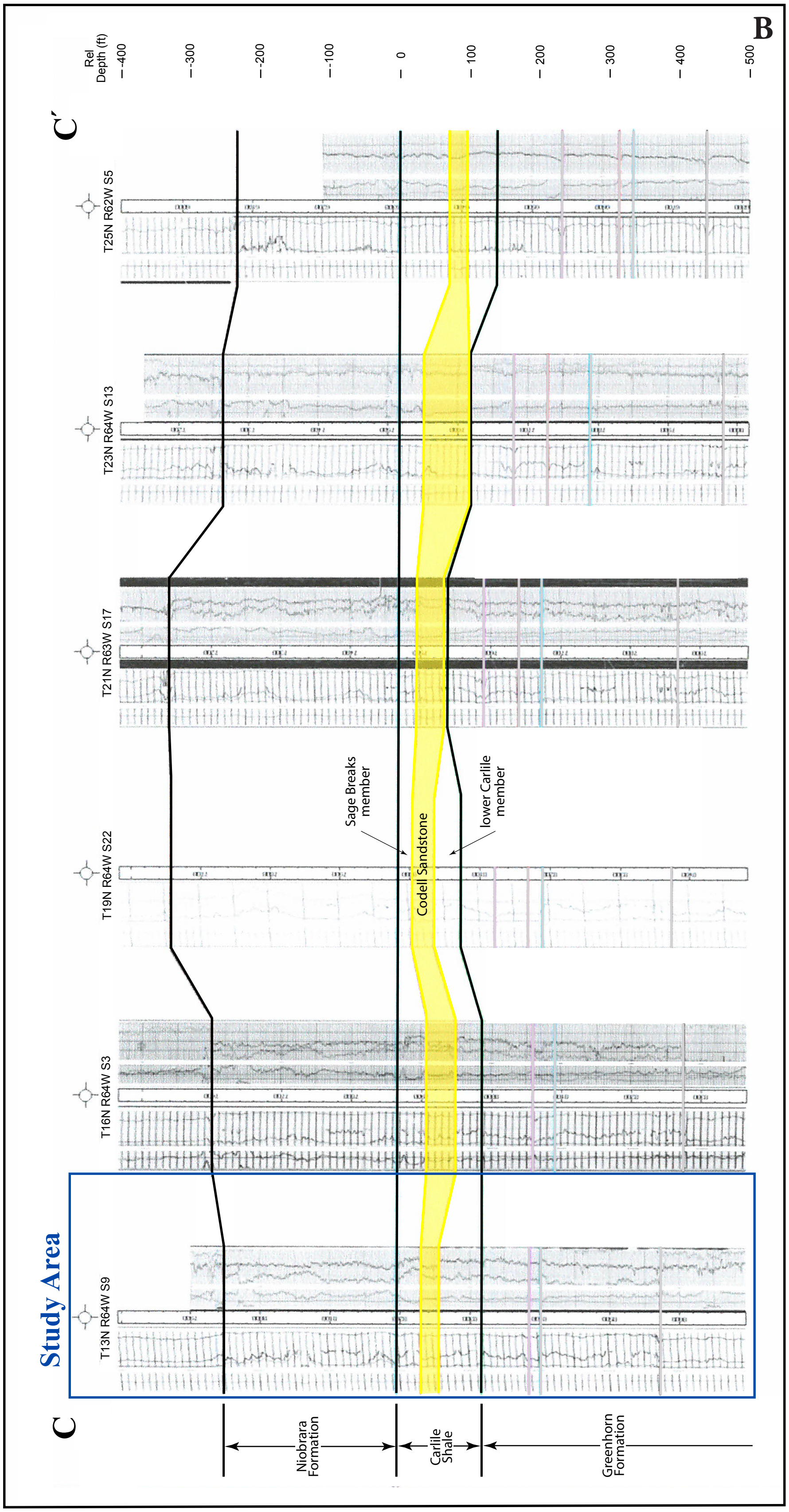


Figure 2 continued.

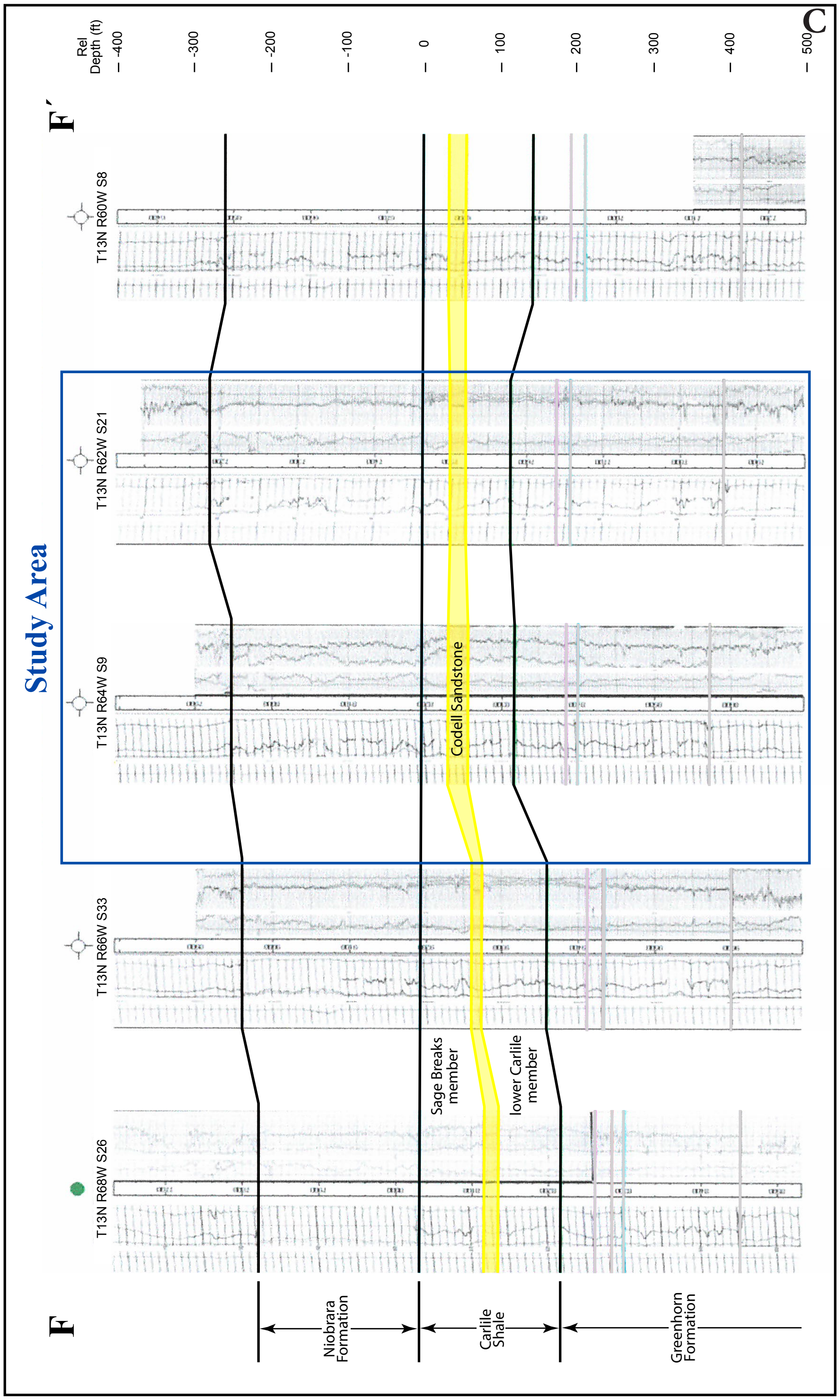


Figure 2 continued.

Previous work

The majority of previous Codell Sandstone investigations in the Denver Basin have been focused in Colorado. For the purpose of this report, only highlights of applicable studies within the Wyoming portion of the Denver Basin are discussed.

Much early work on Turonian formations in the northern Denver Basin had minimal reference to the Codell Sandstone or generalized it within the framework of the Carlile Shale and surrounding formations. One of the first references to the Codell Sandstone was by Bass (1926), who used it to describe the upper sandstone of the Carlile Shale in Kansas. Burk (1956) briefly mentioned the Codell Sandstone as being the southeastern Wyoming equivalent to the Turner sandy member seen in the Powder River Basin. One of the first maps showing the general Denver Basin structure in Wyoming and Nebraska was a structure contour map of the top of Mississippian/base of Pennsylvanian strata by Anderman and Ackman (1963). Martin (1965) extended this mapping by further outlining the basin structure with isopach maps of Mississippian, Pennsylvanian, Permian, Triassic, and Jurassic sediments, and the D and J Sands of the Lower Cretaceous. Kitely (1978) published the first detailed cross-sections delineating the top of the Carlile Shale in Wyoming.

Weimer and Sonnenberg (1983) produced one of the first comprehensive Codell Sandstone studies that included the Wyoming portion of the Denver Basin. This study includes structure contour and isopach maps, characteristic log signatures, and cross-sections of the Codell Sandstone. It also discusses a depositional model for the Codell and its potential as a petroleum reservoir.

Merewether and others (1979, 2007, 2011) and Merewether and Cobban (1986) established age ranges for Turonian sediments in the Denver Basin using biostratigraphic faunal zones. These biostratigraphic data were related to unconformities within the Carlile Shale and other Cretaceous strata to develop a regional structural history. Weimer (1984) also investigated the unconformity at the base of the Codell/upper Carlile, again relating it to regional sea level changes and associated tectonic activity. Brief discussions of how regional tectonics could subsequently influence potential petroleum sources and migration were also included in these studies.

One of the first evaluations of the Codell Sandstone as an oil reservoir was by Nolte (1963). Based on the insignificant production from the Codell at the time, Nolte dismissed the Codell as being an economical reservoir. The earliest discussion of source rocks in the Denver Basin is found in Clayton and Swetland (1980), which identified the Niobrara Formation, Graneros Shale, Greenhorn Formation, and lower Carlile as likely origins of the oil found in surrounding formations. Rice (1984) discussed the hydrocarbon types found in the Niobrara Formation and Codell and the limit of thermally mature Niobrara source rock, but this work concentrated mainly on data from Colorado. Sonnenberg (1985) noted unproductive Codell exploration efforts using vertical wells and targeting stratigraphic traps southeast of the Hartville uplift. Higley and others (1996) and Higley and Cox (2007) combined the Codell Sandstone and the Niobrara Formation in their evaluation of oil and gas potential of the Denver Basin. Towler and Gao (2011) include a structure contour map of the Codell Sandstone in a model of the Niobrara Formation reservoir in Silo field, but no discussion of it as an oil reservoir.

Anderson (2011) provides perhaps the most thorough examination yet of the Codell Sandstone within the Wyoming portion of the Denver Basin. His work included outcrop, core and thin-section descriptions, measured sections, 11 cross-sections (creating a grid of six east-west and five north-south cross-sections), and multiple structure contour and isopach maps of the Greenhorn Formation, lower Carlile Shale, Codell Sandstone, Sage Breaks Shale, and Niobrara Formation. He examined the burial history of this portion of the Denver Basin and examined the potential of the Codell as a productive hydrocarbon reservoir.

Multiple presentations and posters by Smith (2015), Smith and others (2014, 2015), and Sterling and others (2015, 2016) also focus on the Codell Sandstone in the northern Denver Basin. These publications include the drilling history and current spacing of Codell-producing wells in Wyoming, well completion specifics, fluid analysis, core and thin-section descriptions, and associated porosity and permeability analyses. Cross-sections of the Niobrara, Fort Hayes, Codell, and Carlile; thermal maturity, isopach, and structure contour maps; and source rock discussions are also presented, along with evidence that longer laterals are an important factor in developing oil from the Codell Sandstone.

CODELL PRODUCTION IN THE NORTHERN DENVER BASIN

Production overview

Production data were downloaded from the WOGCC's March 28, 2017, production report (1978-03282017_Production) and filtered for all Codell Sandstone oil production from horizontal wells in Laramie County, Wyoming. These filters were applied because Laramie County has the vast majority of recent Codell Sandstone oil development in the northern Denver Basin. In addition, very few vertical wells have produced from the Codell Sandstone and those that did were completed using different, outdated technology that would not be an equivalent comparison to current completion practices. Wells included in this study may also produce from additional reservoirs, but that production was not of interest or evaluated.

As of March 2017, 119 wells from six different operators have produced oil from the Codell Sandstone in the northern Denver Basin. These 119 wells define an approximately 640-square-mile study area east of Cheyenne and the basin axis (fig. 3). The earliest-producing well came online in 2012. Cumulative production was summed for all wells, and each well's first 3, 6, 9, 12, and 18 months of production was calculated by omitting all months with no production. If a well's first month online did not produce for at least 15 days, that production was added to the next three months of successive production, resulting in slightly more than three months production. It should be noted that newer wells may not have produced long enough to provide data for all time intervals, resulting in their omission from any or subsequently longer first-months plots. Publicly available data on initial completion and production tests, the number of frac stages, total slurry volume, and the total amount of proppant used to complete each well were also collected from WOGCC. Simplified horizontal well design parameters (lateral direction and lateral length) were calculated from WOGCC surface hole and bottom hole locations.

To preliminarily identify which Codell-producing wells are most successful, each well's initial, first 3, 6, 9, 12, and 18 months of oil production was compared to their respective cumulative production (fig. 4) and their respective average rate of production (fig. 5). Production rate was calculated by dividing cumulative production by the total number of days the well was reported as producing, resulting in an average number of barrels produced per day. Initial production (figs. 4A and 5A) was plotted on a different scale than the first-months graphs.

Full names of operator abbreviations can be found in table 1. The Excel spreadsheet attachment contains all well drilling, completion, and production data used in this report.

Table 1. Operator abbreviations.

Operator abbreviation	WOGCC operator full name
Anadarko	Anadarko E&P Onshore LLC
Bill Barrett	Bill Barrett Corporation
EOG	EOG Resources Inc
FH	FH Petroleum Corp
HRM	HRM Resources II LLC
Kaiser	Kaiser Francis Oil Co
Longs Peak	Longs Peak Resources LLC
Panther	Panther Energy Company II LLC
Samson	Samson Exploration LLC
Ward	Ward Petroleum Corporation

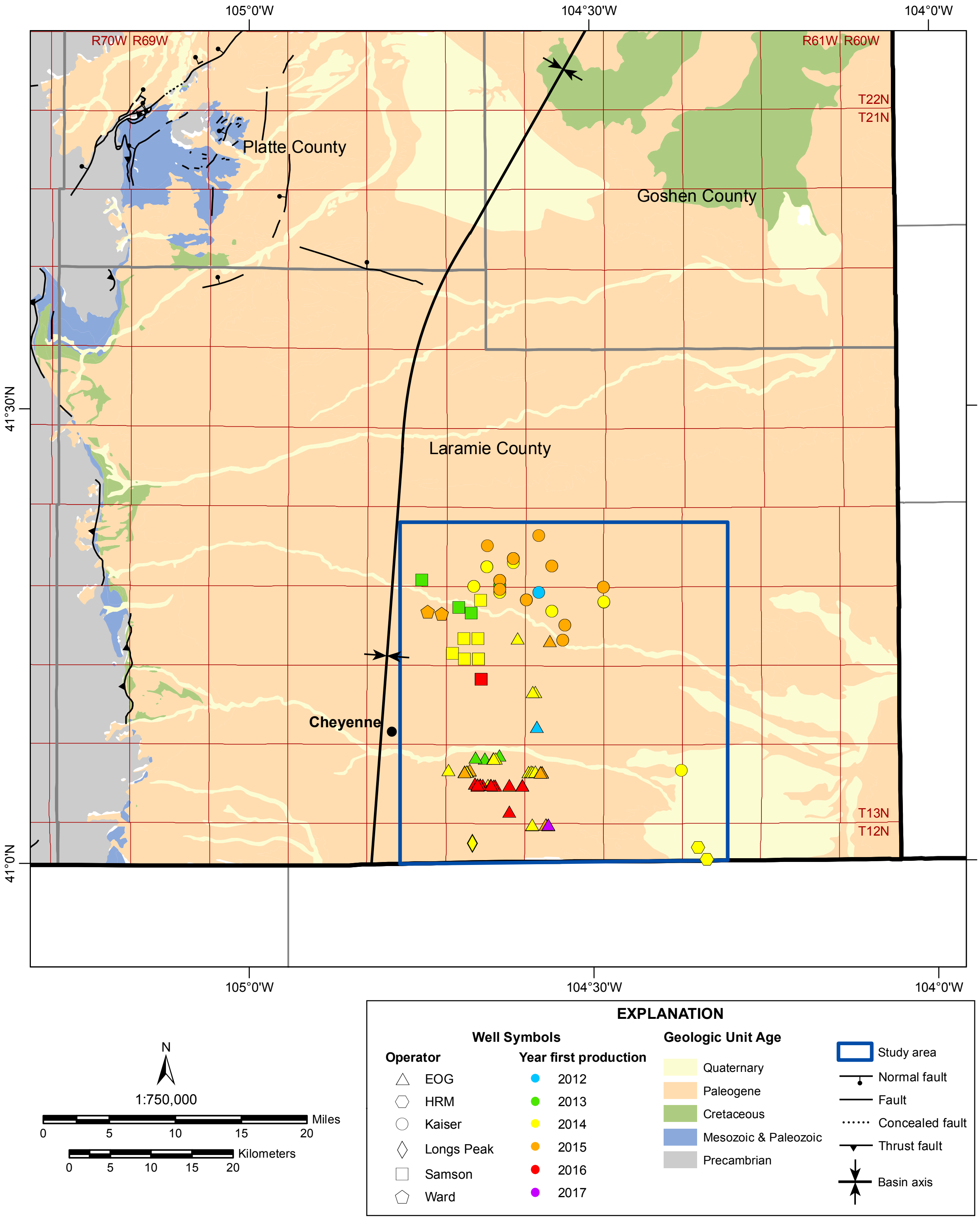


Figure 3. Generalized bedrock geology map of the northern Denver Basin, modified from Love and Christiansen (1985). The blue rectangle indicates this report's study area. Wells included in this study are colored by year of first production, and well operator is represented by symbol shape.

Initial and First Months Oil Production vs. Cumulative Oil Production

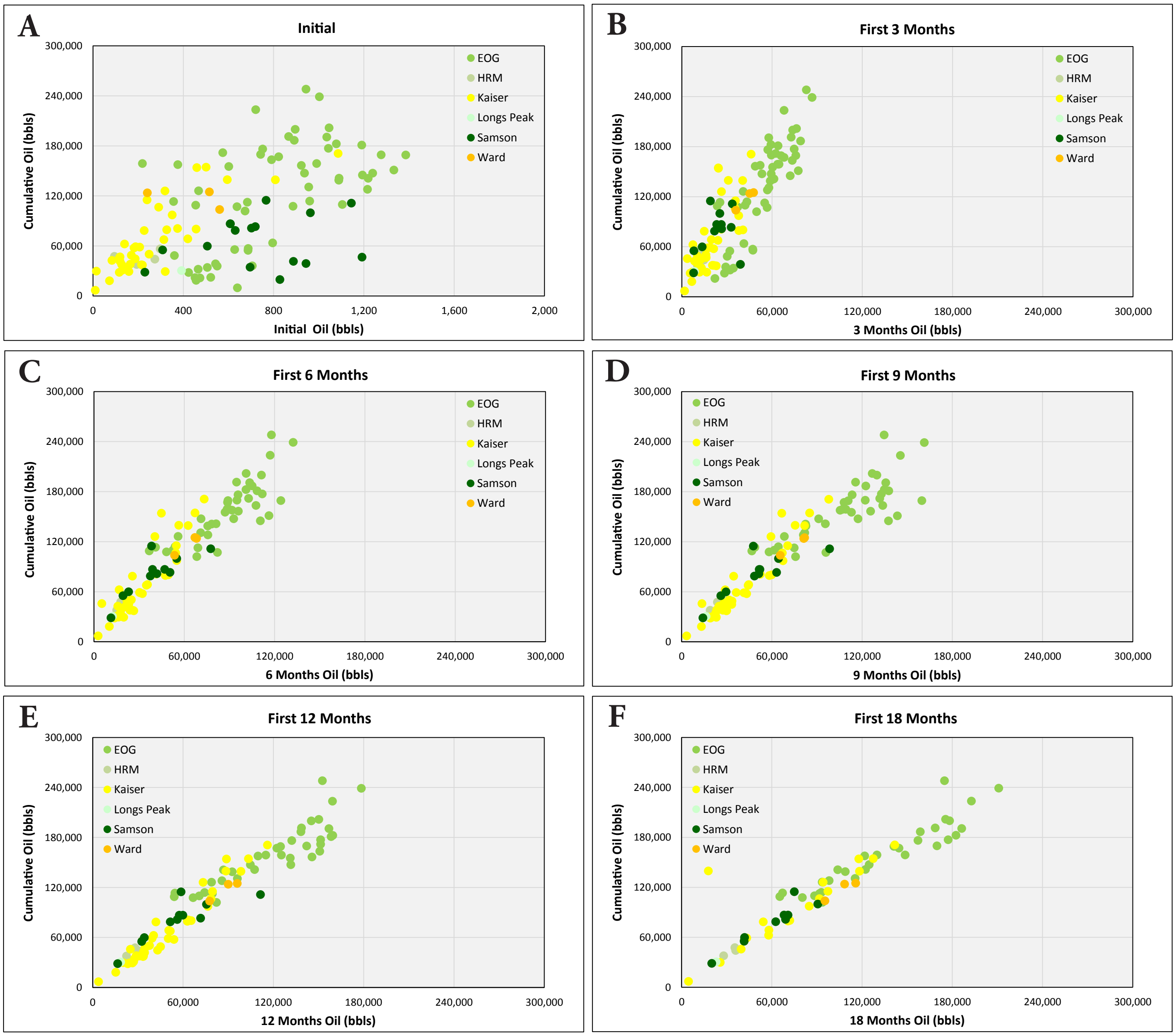


Figure 4. Cumulative Codell Sandstone oil production versus (A) initial oil production and oil production for the first (B) 3 months, (C) 6 months, (D) 9 months, (E) 12 months, and (F) 18 months.

Initial and First Months Oil Production vs. Average Daily Oil Production

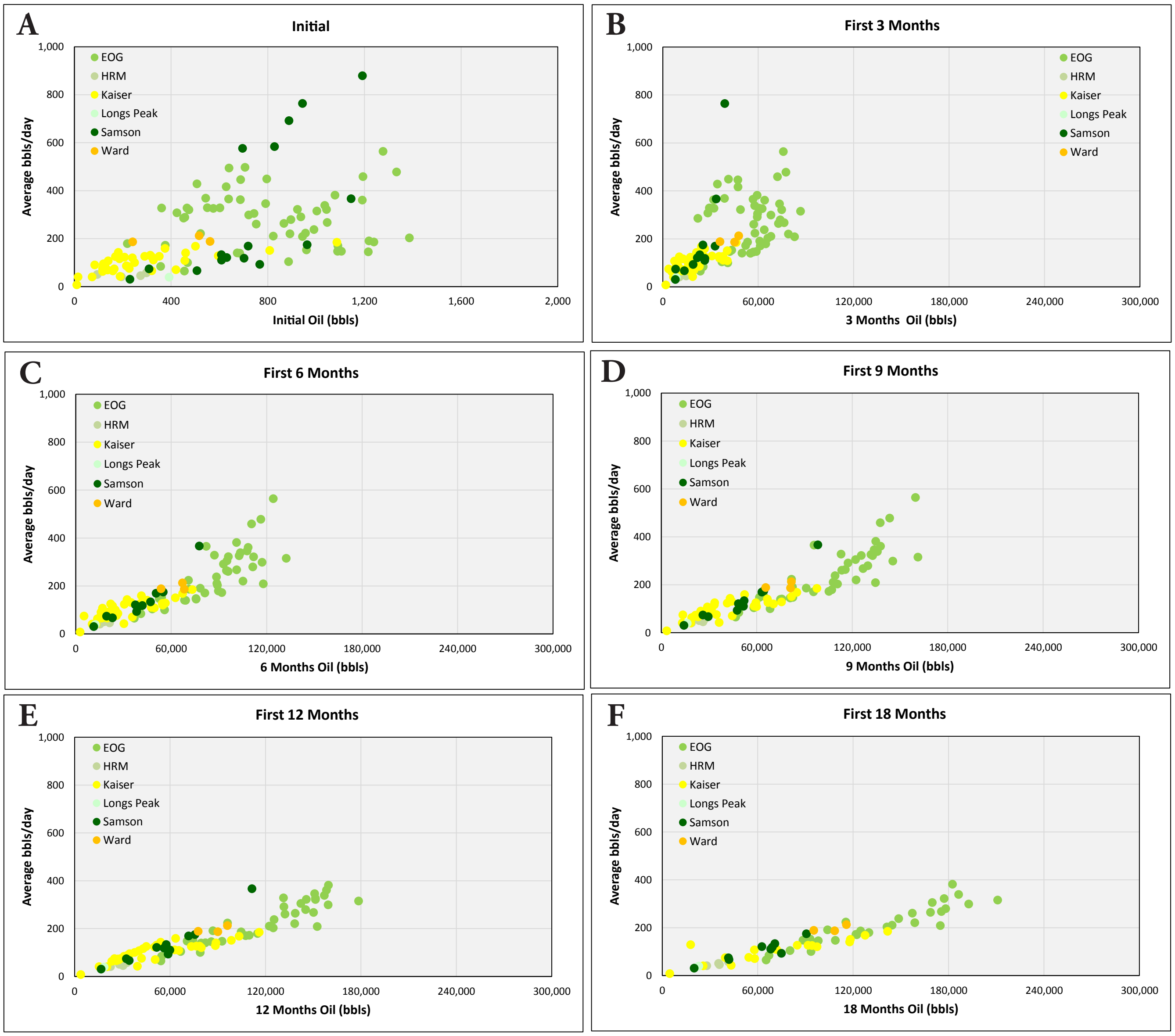


Figure 5. Average daily Codell Sandstone oil production versus (A) initial oil production and oil production for the first (B) 3 months, (C) 6 months, (D) 9 months, (E) 12 months, and (F) 18 months.

All first-months plots on these figures display a positively-sloped linear trend, but the trend becomes more defined for progressively longer time intervals. This confirms that wells that ultimately have the highest cumulative production also consistently produce the most oil during their first months of production. The slope of the line also increasingly shallows, reflecting a decline in the average number of barrels/day per well. The plots indicate that some operators appear to have achieved consistently better well performance than others.

To further investigate operator-specific production, the three operators with the most Codell-producing wells between 2012 and 2016 were identified. Monthly Codell oil production for each of these operators' wells are shown in figure 6. Besides highlighting a large difference between operators' peak monthly production, figure 6 also suggests that some operators were able to slow the rapid production decline common in wells completed in tight sands and shales. Wells beginning production before 2015 have much narrower peaks than wells first producing in 2015-2016. The broader width of the newer wells' monthly trends indicate operators have determined how to extend their wells' peak production.

In order to determine if unit thickness, structural position, and other traditional geologic factors affect well success in the northern Denver Basin, the initial, first-months, and cumulative oil production were input into an ArcGIS spatial analyst inverse distance weighted (IDW) tool using default parameters. This generated contour rasters that spatially interpolate between wells and areas of highest and lowest production. The rasters were further smoothed using ArcGIS' Filter tool. The first-months rasters were symbolized using the same scale as the cumulative raster so that the increase in oil production over time can be more easily visualized. Each production raster was then overlaid with both Codell Sandstone isopach contours and structure contours (unit depth) developed by Anderson (2011; figs. 7-13). Anderson's (2011) isopach contours are based on individual well log thicknesses and no correction for the minimal regional dip was noted.

No correlation is observed between the highest-producing wells and the reservoir depth or thickness, as some of the best-producing areas are in the thinnest areas of sandstone and some of the least productive wells are located in the thickest sections. Additionally, the best-producing wells are either downdip from or along strike with wells that show lower production. Visually, production from the Codell is consistently highest in the southern portion of the study area, but is also associated with long-lateral, north-south wells, making it unclear whether the high production is due to operator-specific practices. To further investigate how drilling and completion affect production, these practices are compared to oil production in detail in the following sections.

Monthly Oil Production of Three Most Active Operators

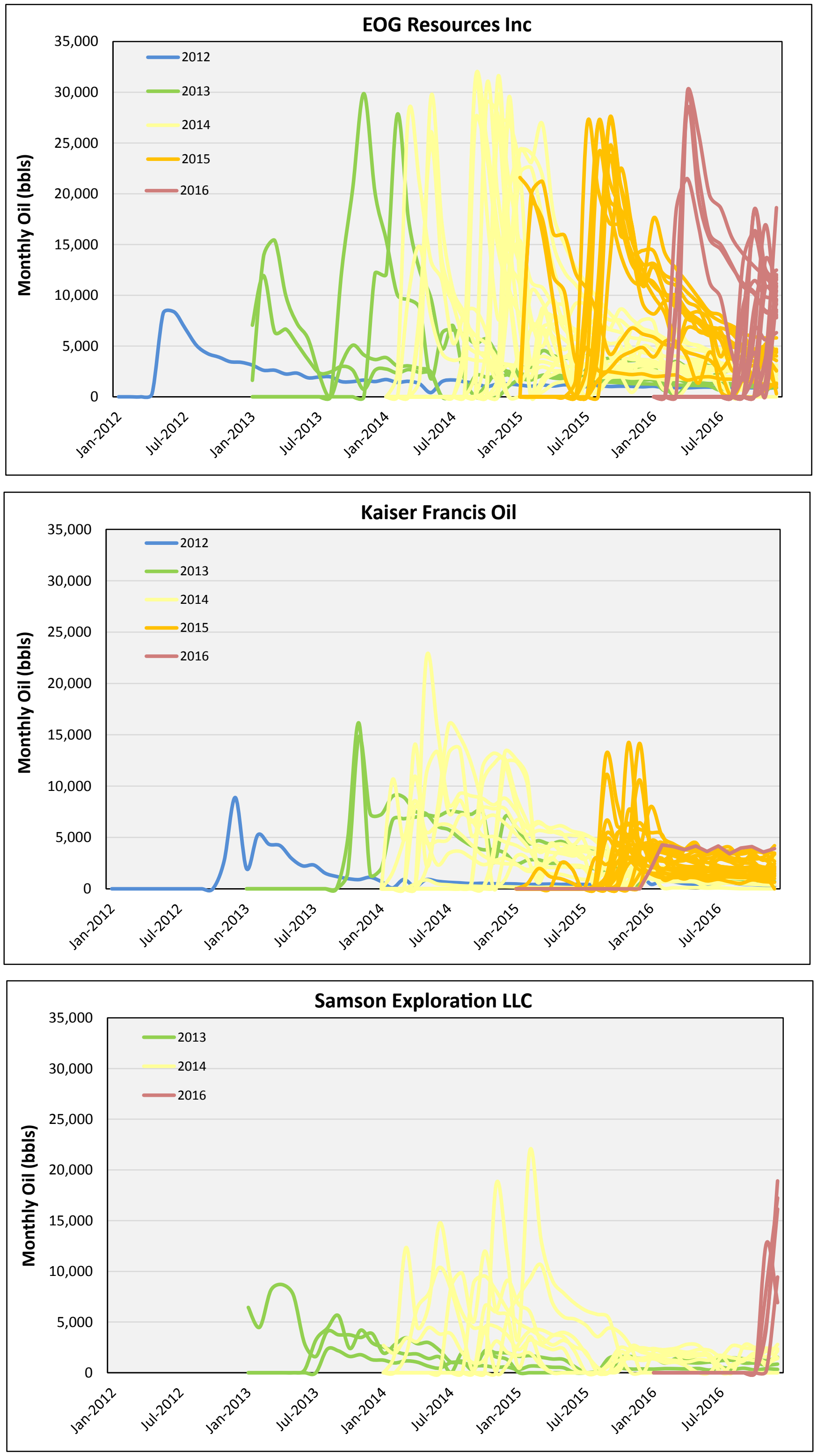


Figure 6. Monthly Codell Sandstone oil production for the three most currently active Codell Sandstone operators in the northern Denver Basin. The earliest Codell Sandstone-producing well in the basin came online in 2012, and production is shown through 2016. Wells are colored by year of first production.

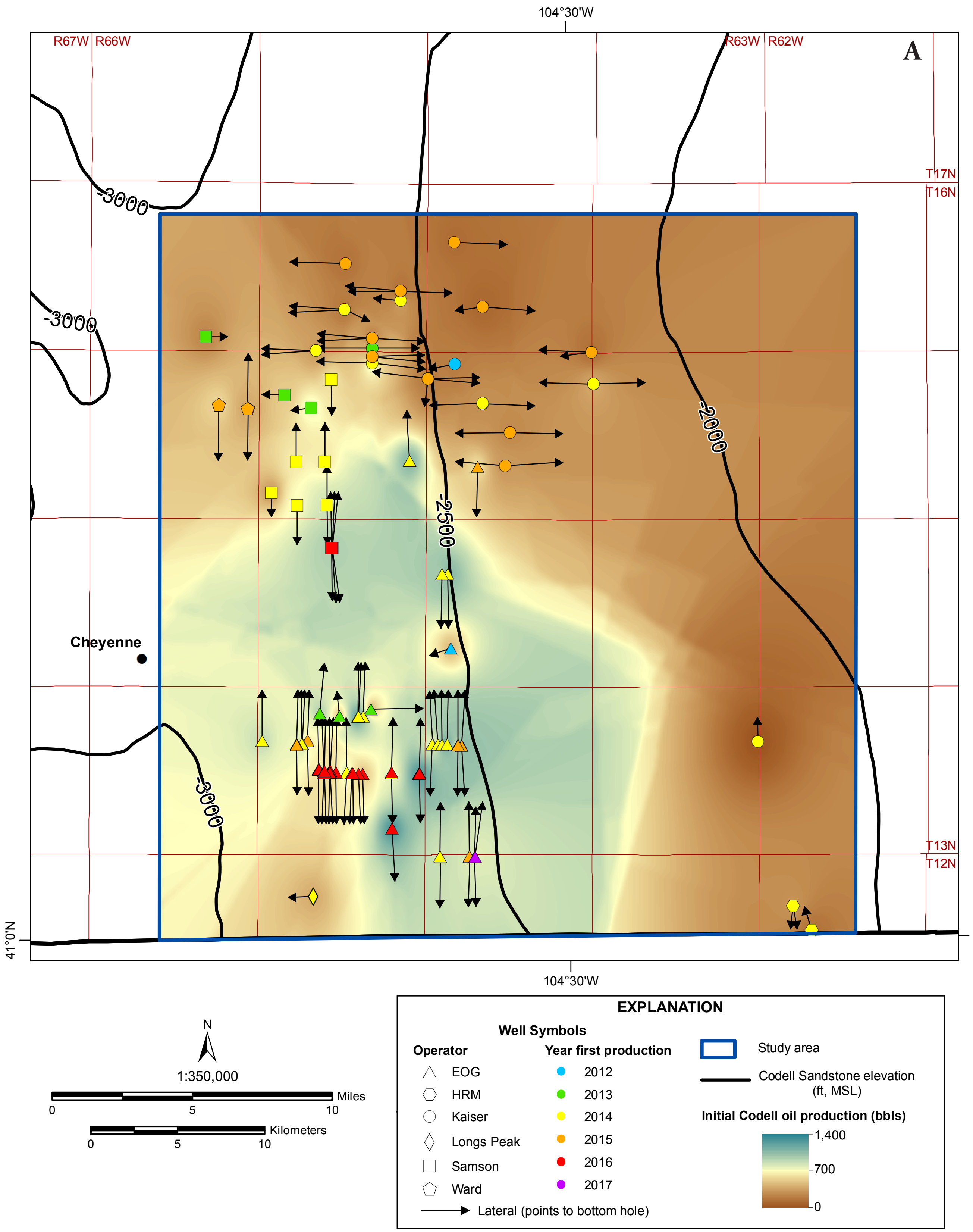


Figure 7. Initial Codell Sandstone oil production contours generated in ArcMap using IDW; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

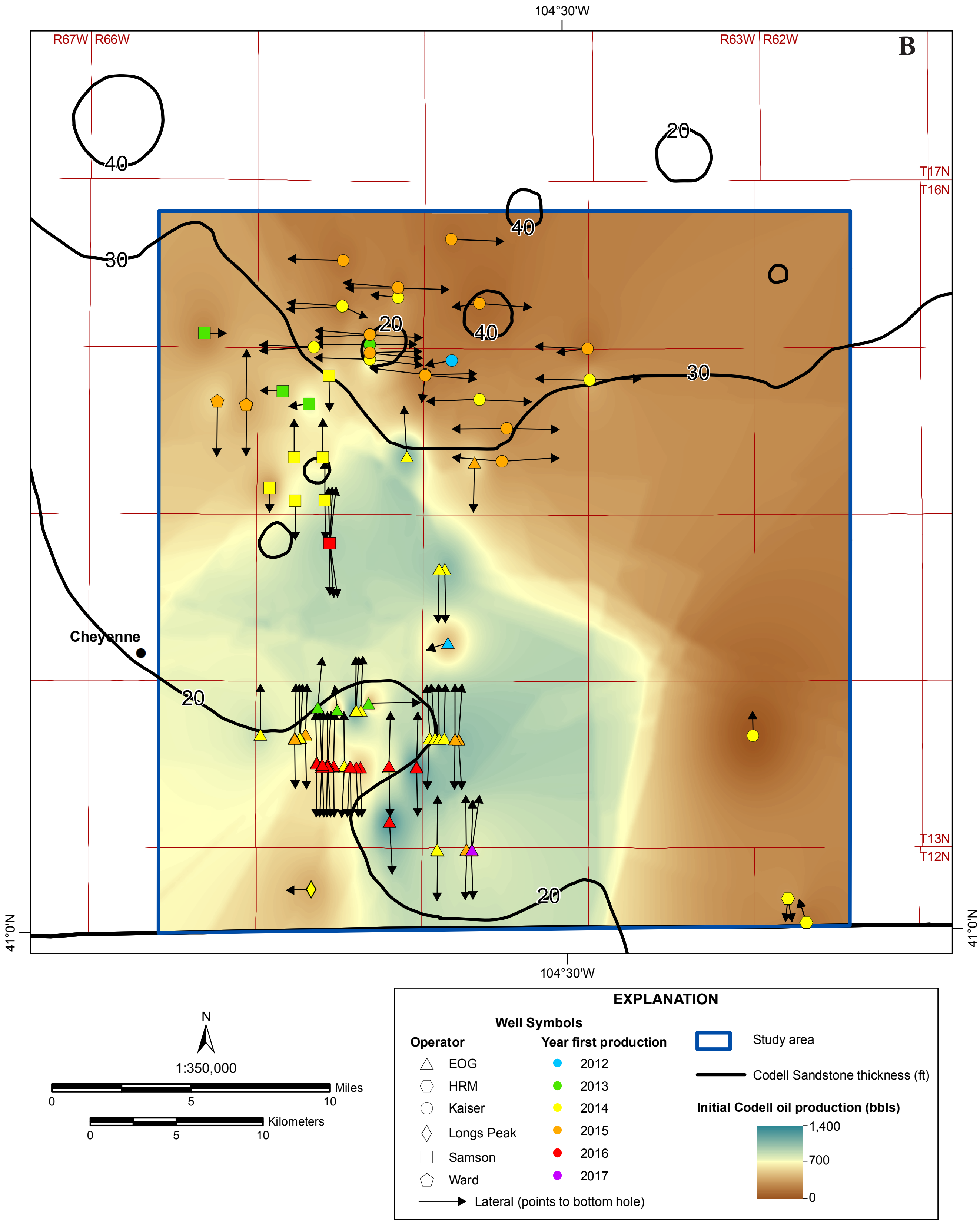


Figure 7 continued.

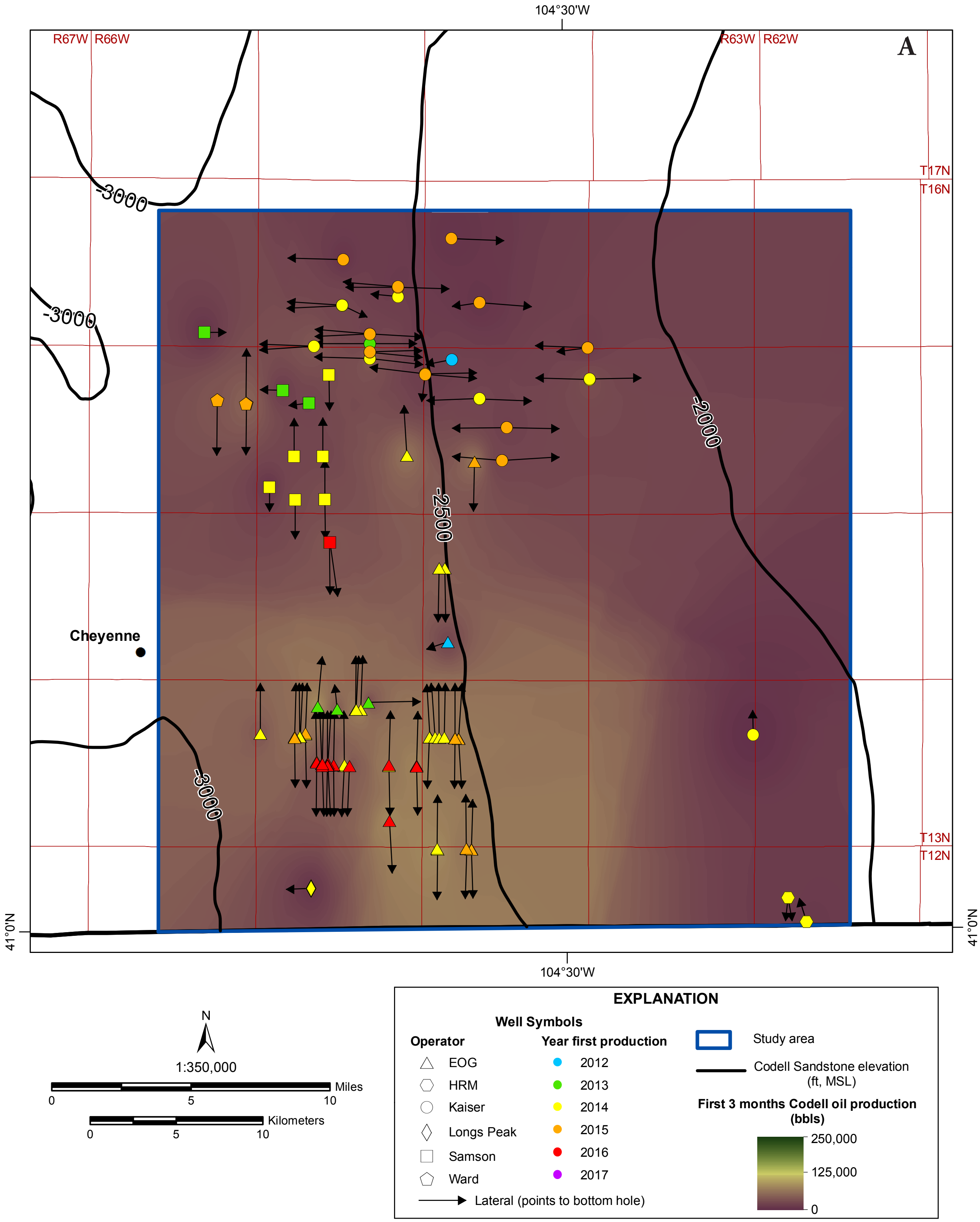


Figure 8. First three months of Codell Sandstone oil production contours generated in ArcMap using IDW and symbolized using cumulative production scale; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least three months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

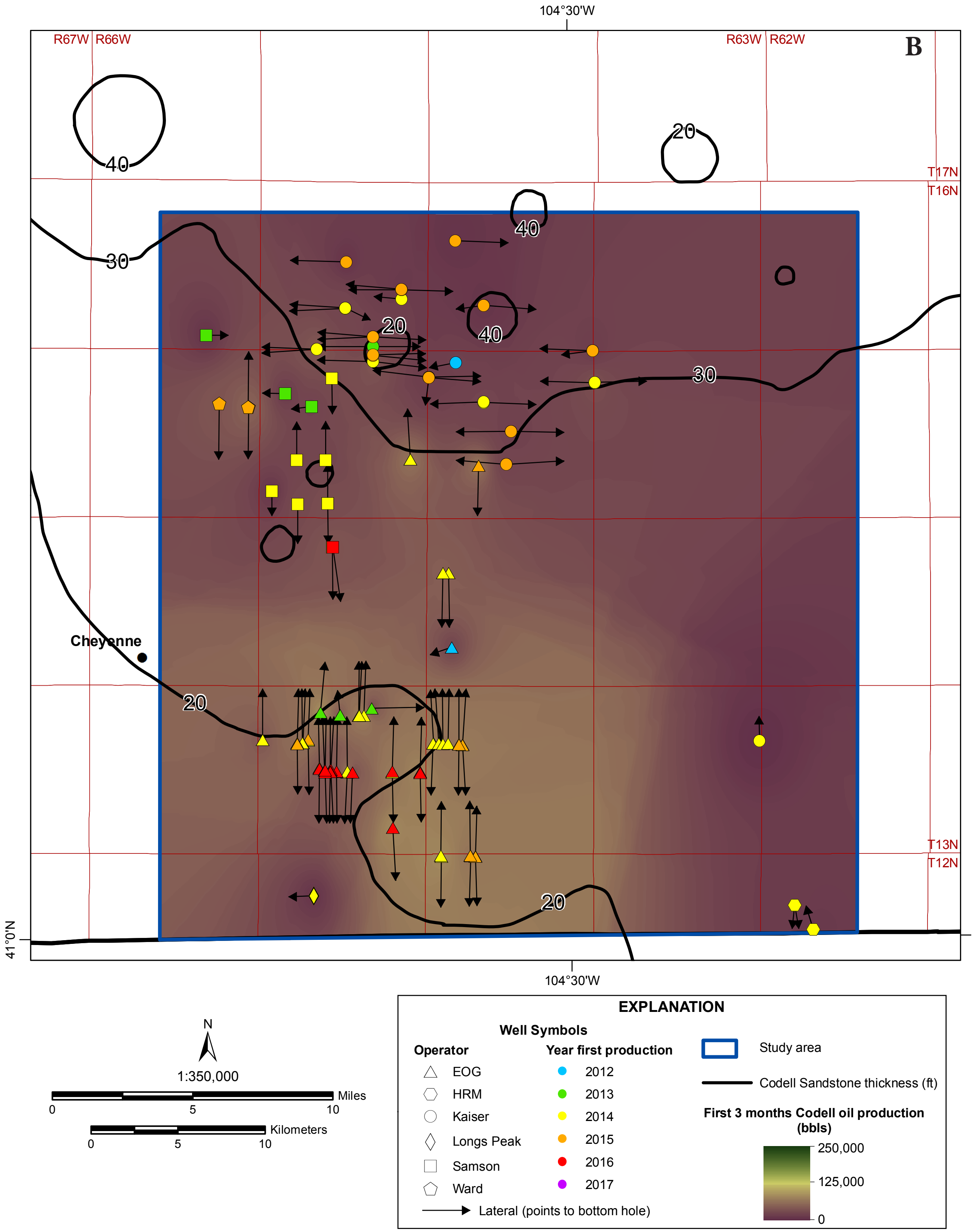


Figure 8 continued.

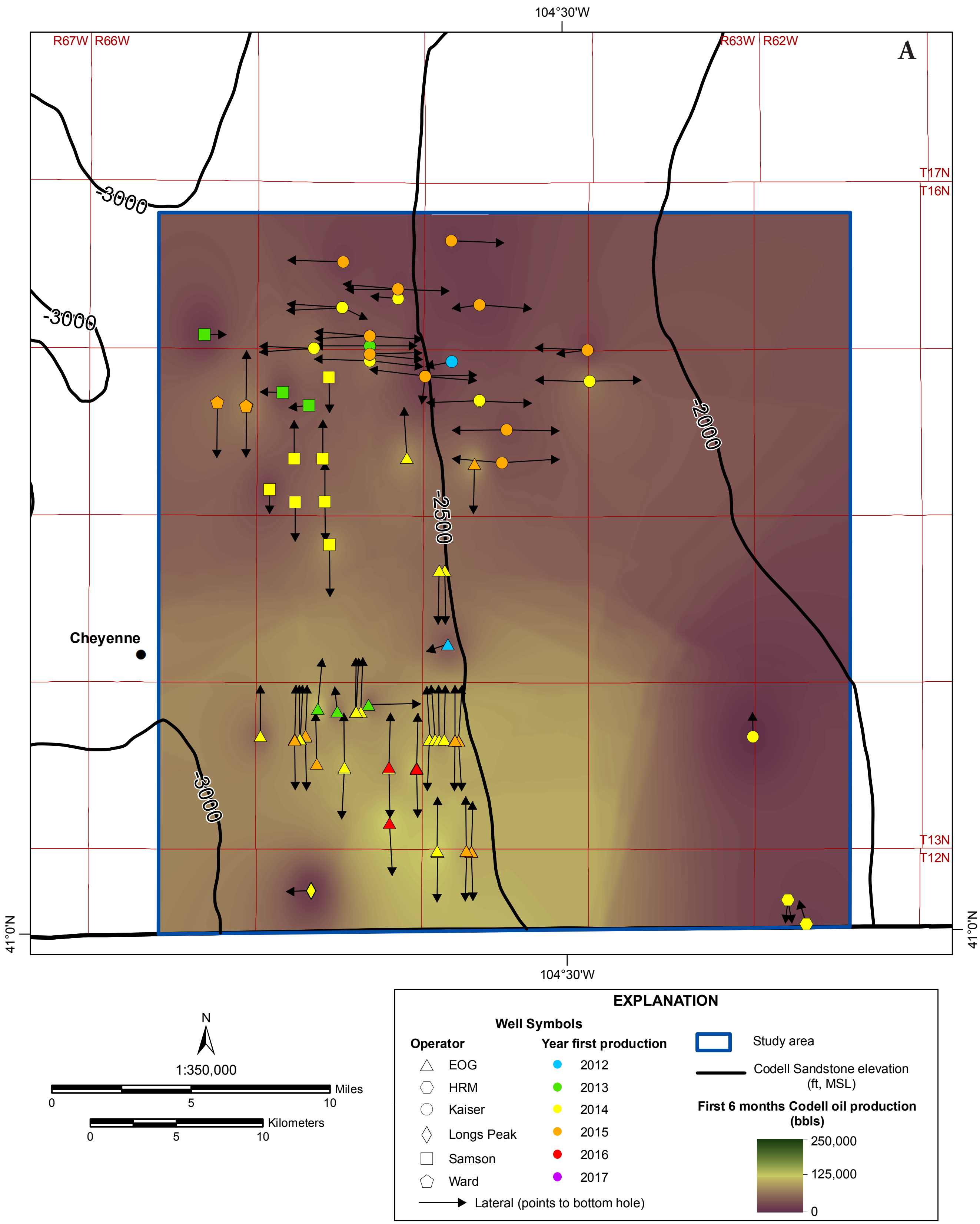


Figure 9. First six months of Codell Sandstone oil production contours generated in ArcMap using IDW and symbolized using cumulative production scale; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least six months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

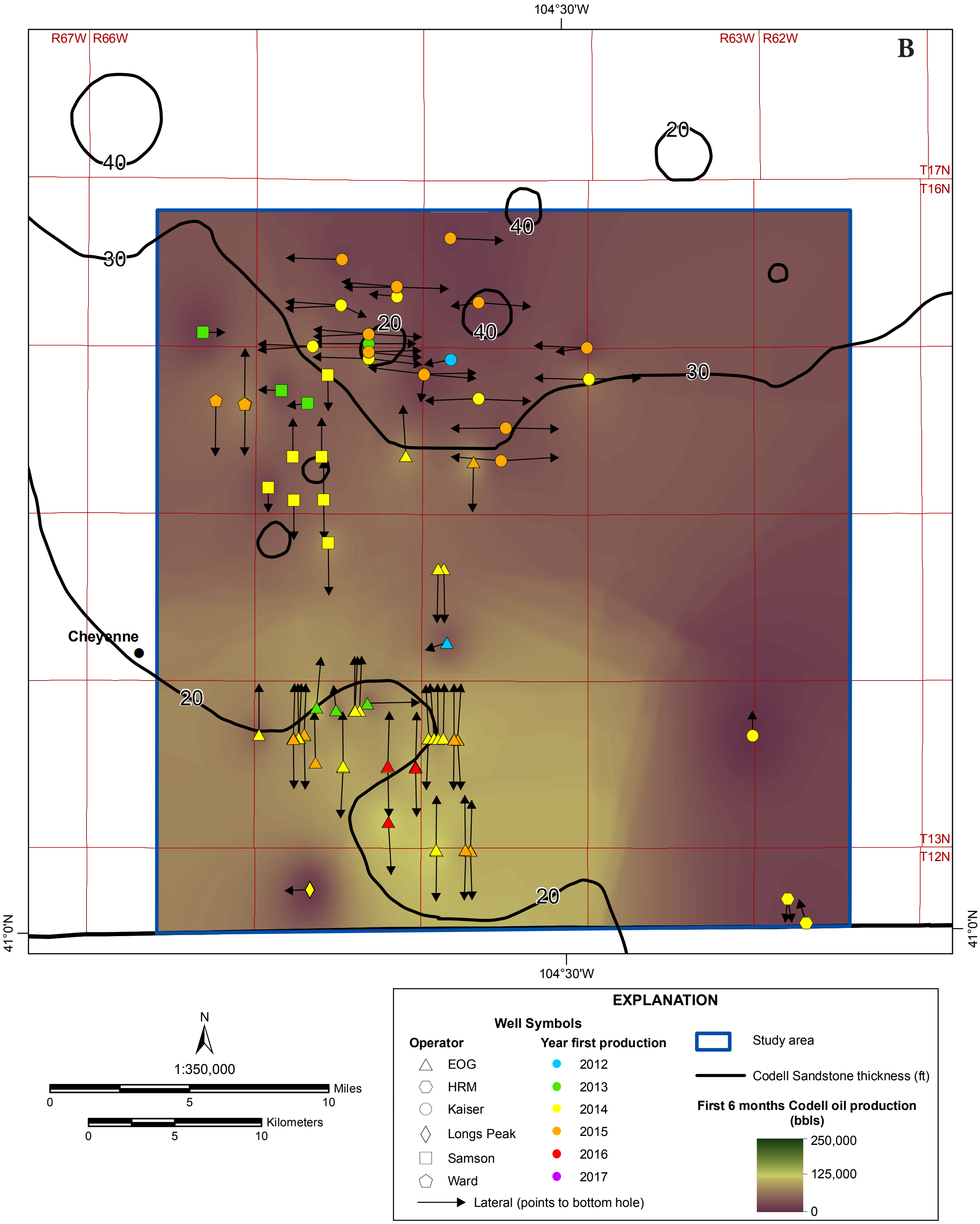


Figure 9 continued.

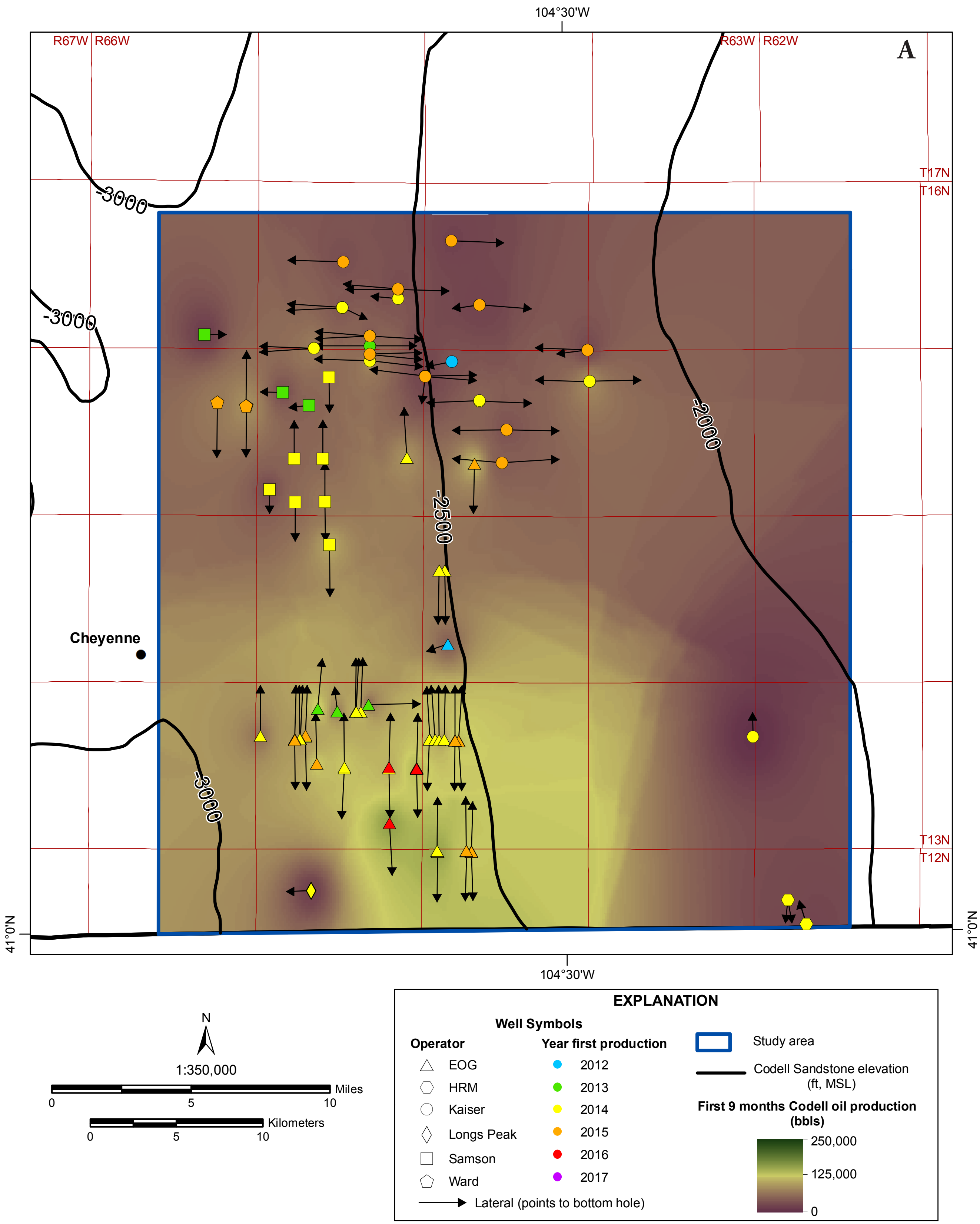


Figure 10. First nine months of Codell Sandstone oil production contours generated in ArcMap using IDW and symbolized using cumulative production scale; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least nine months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

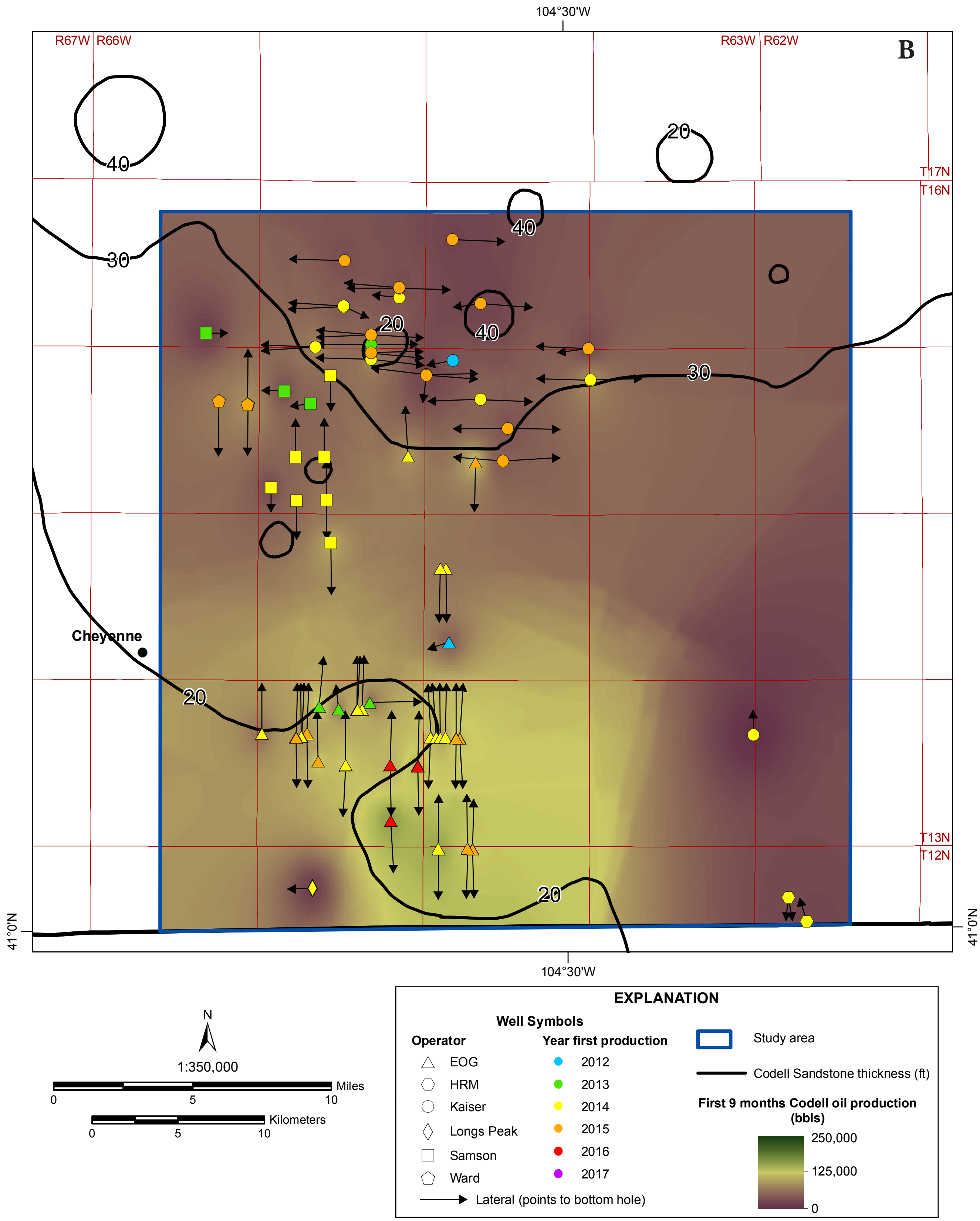


Figure 10 continued.

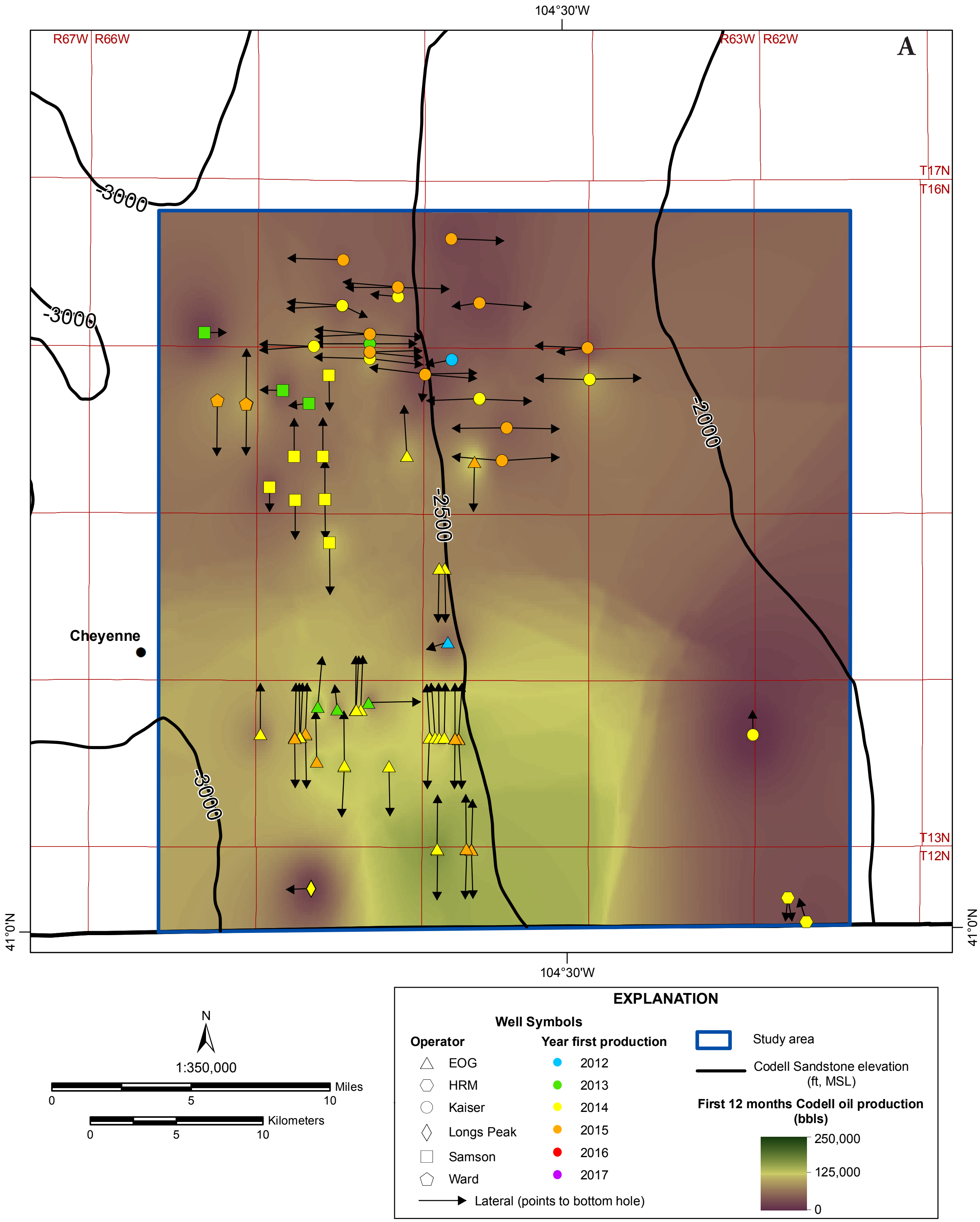


Figure 11. First 12 months of Codell Sandstone oil production contours generated in ArcMap using IDW and symbolized using cumulative production scale; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least 12 months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

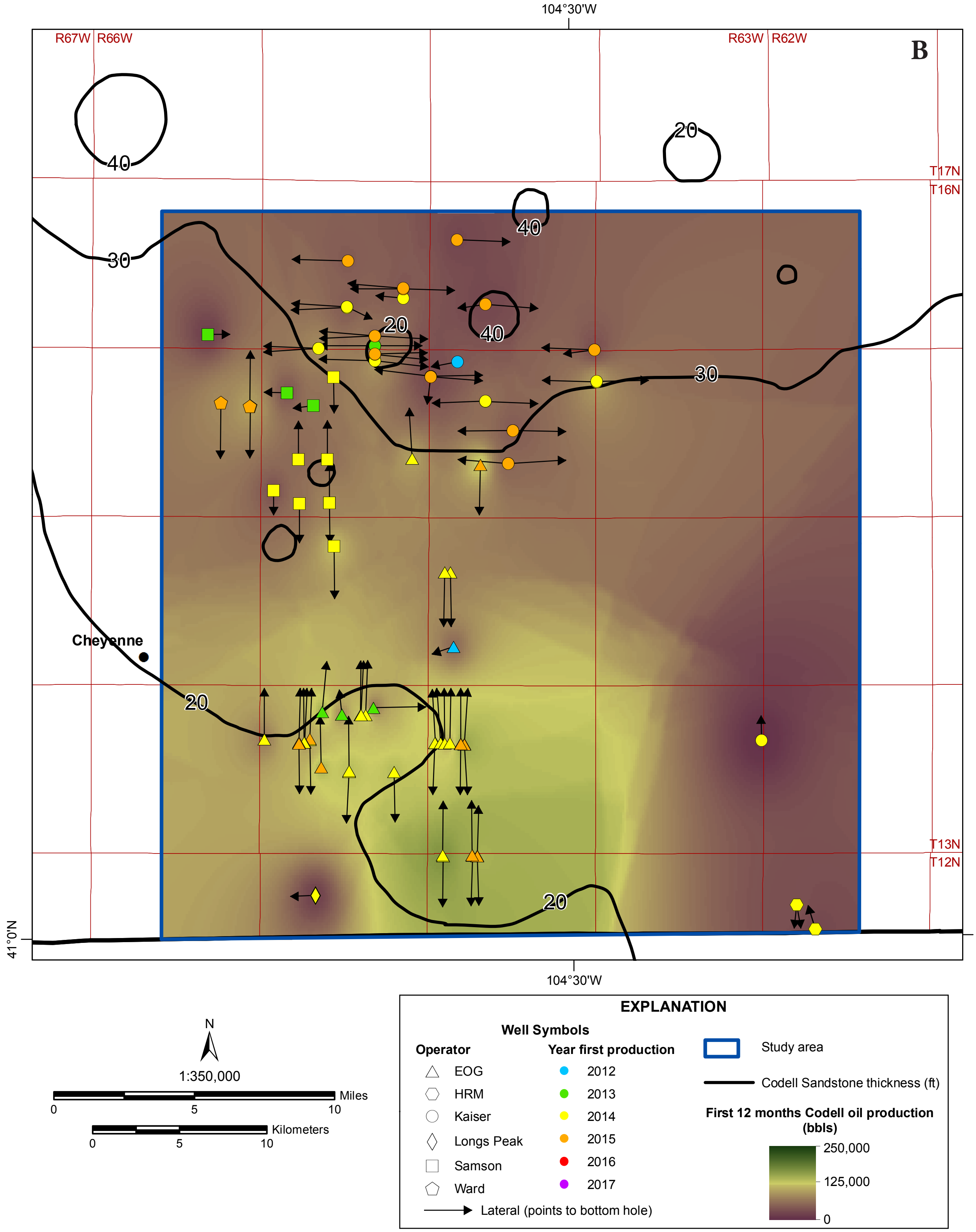


Figure 11 continued.

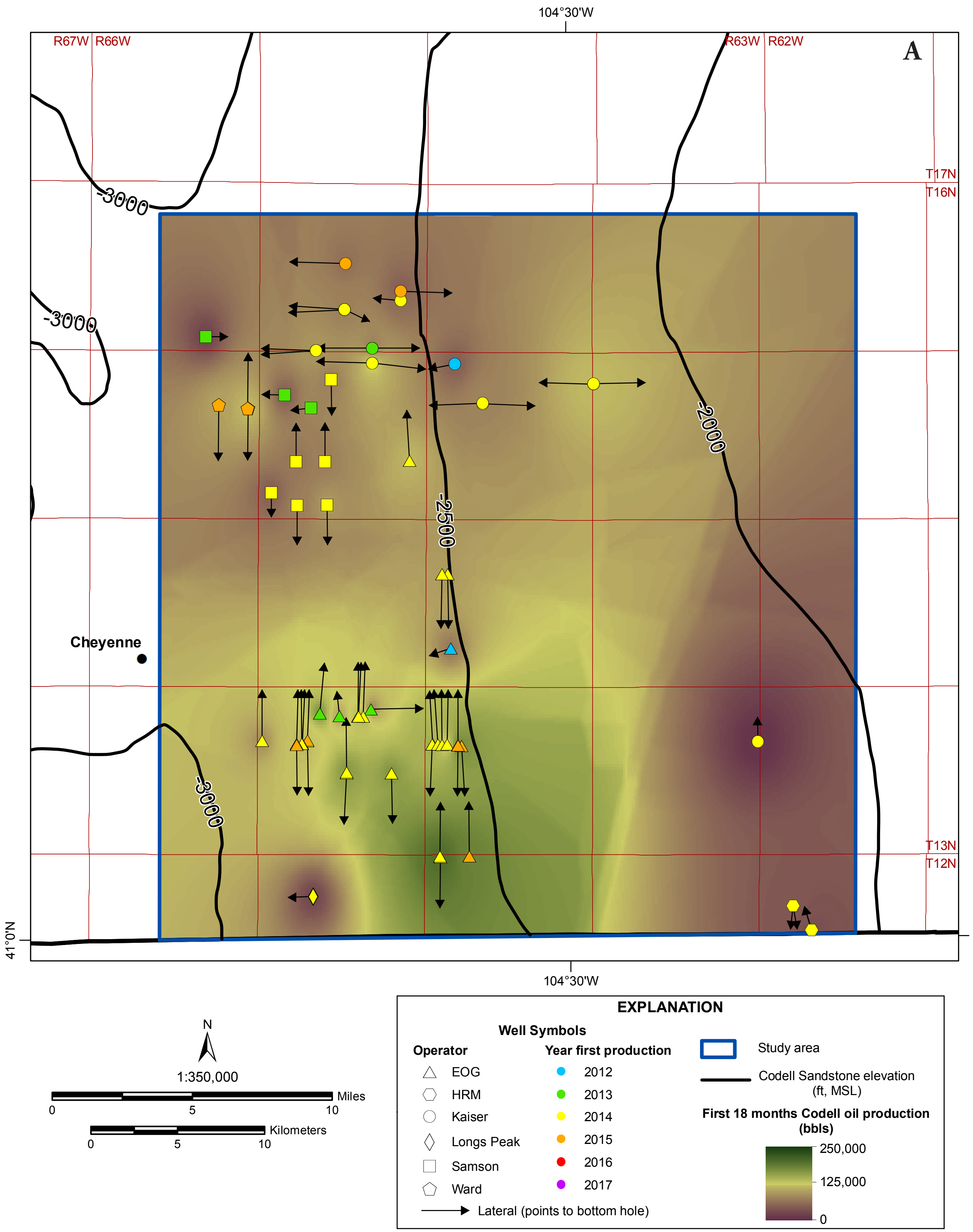


Figure 12. First 18 months of Codell Sandstone oil production contours generated in ArcMap using IDW and symbolized using cumulative production scale; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least 18 months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

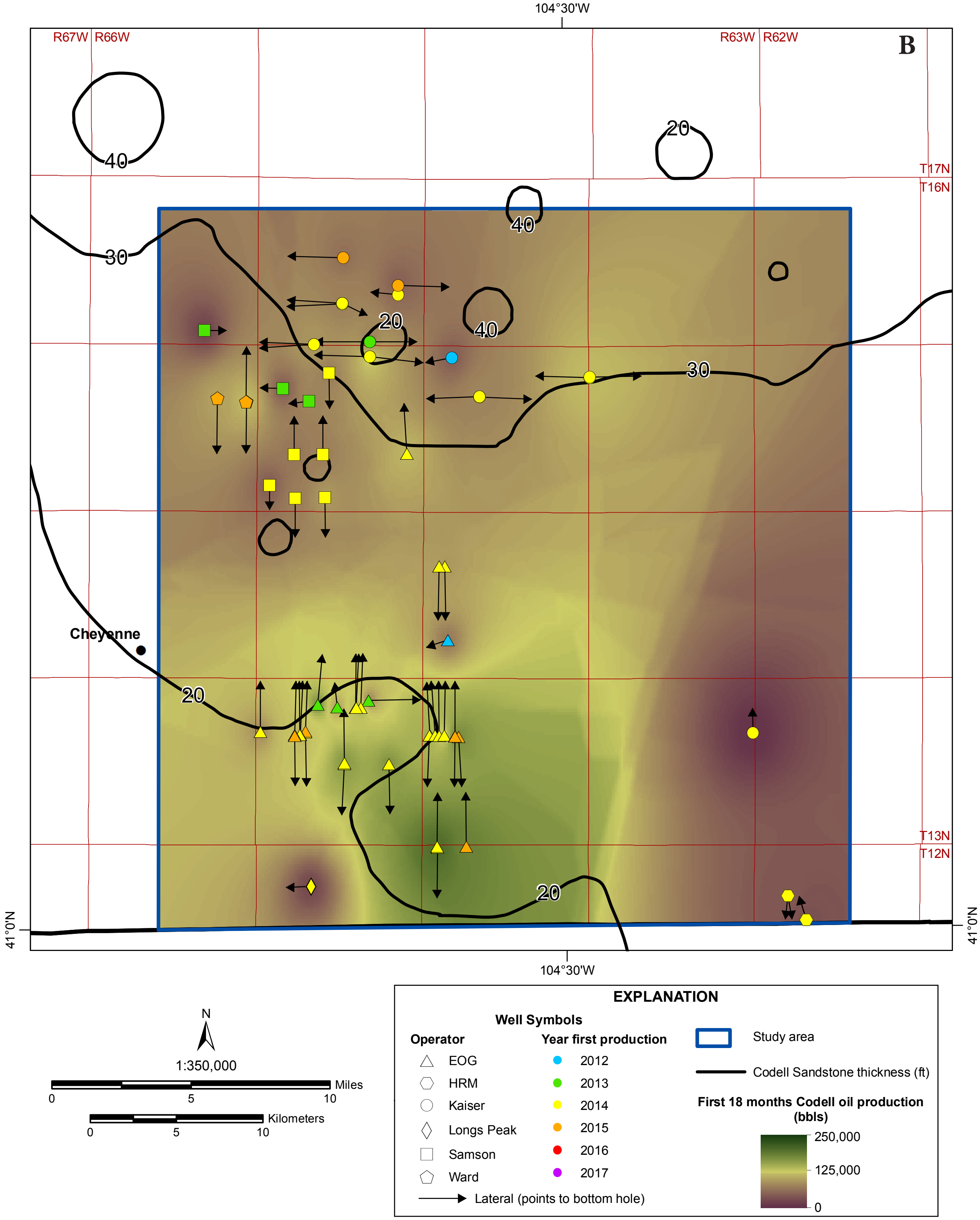


Figure 12 continued.

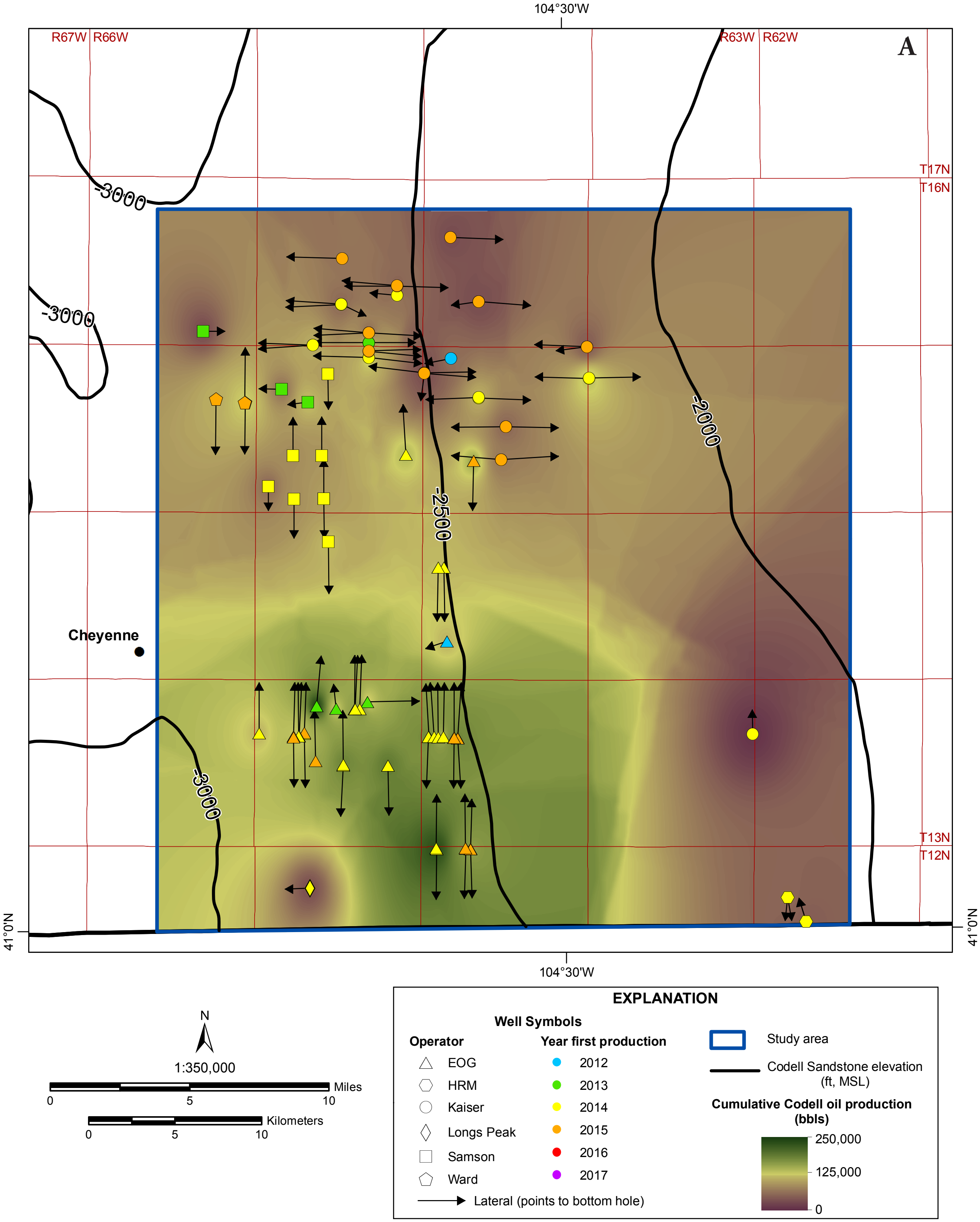


Figure 13. Cumulative Codell Sandstone oil production contours for wells with at least 12 months of production generated in ArcMap using IDW; overlain with (A) depth below mean sea level (MSL) to top of Codell Sandstone (after Anderson, 2011) and (B) Codell Sandstone thickness (after Anderson, 2011). Wells with at least 12 months of production are colored by year of first production, well operator is represented by symbol shape, and an arrow indicates the surface expression of each well's lateral length and orientation.

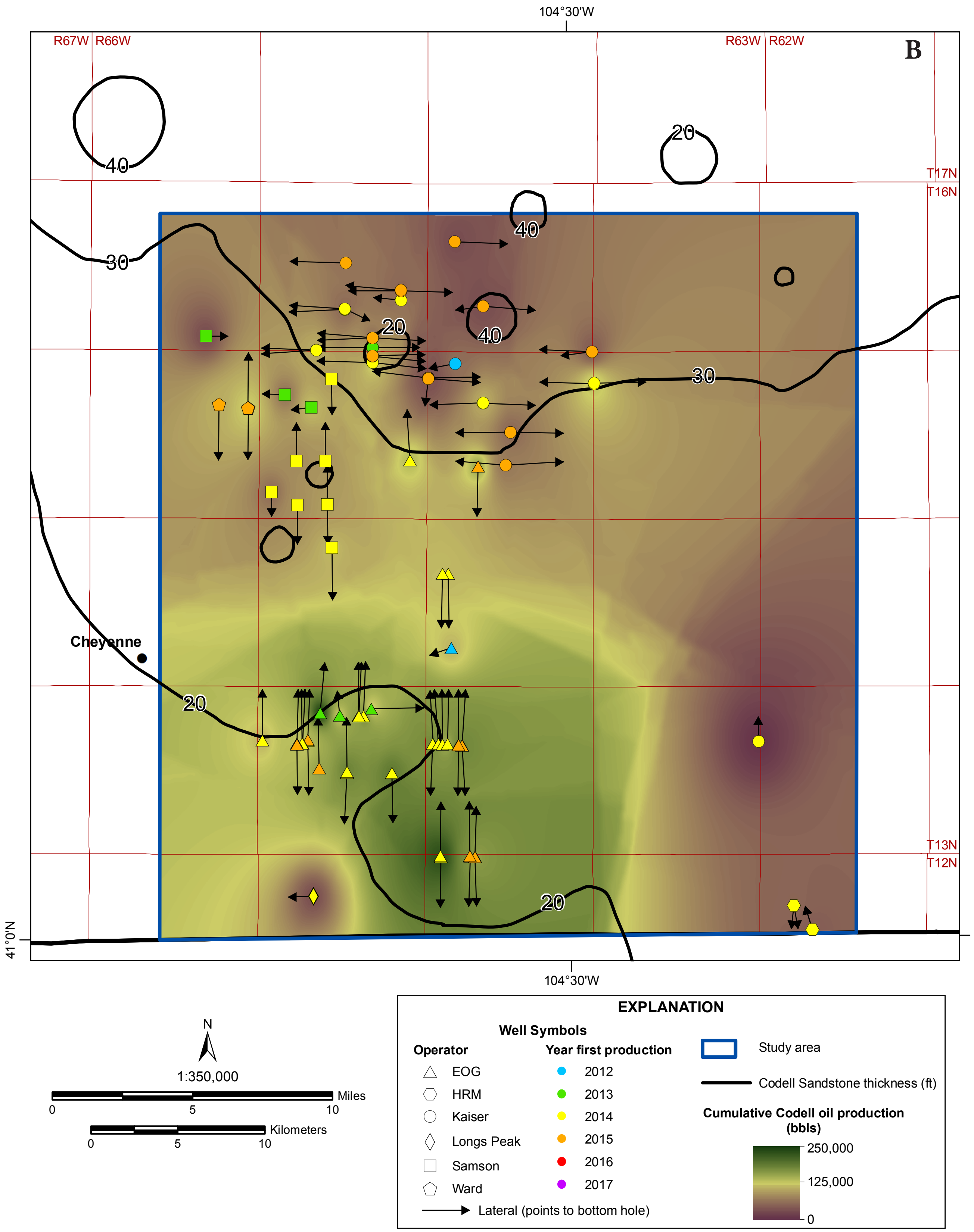


Figure 13 continued.

Lateral length

For general comparison purposes, lateral lengths were calculated as the distance between the well's surface location and the bottom hole/toe location. This report does not take into account curvature of the lateral or directional survey specifics. Although imprecise, this length provides a sufficient approximation of well length.

To compare the productivity of the different lateral lengths, wells were grouped into 1,000-ft categories. The shortest lateral in the study area is just under 3,890 ft, while the longest is more than 10,800 ft. Figure 14 plots production for each length category throughout the life of individual wells. In addition to highlighting that the majority of wells in the study area have lateral lengths greater than 9,000 ft, this figure also indicates significantly superior production of wells drilled to these longer lengths. Even wells owned by the same operator but completed at different well lengths show higher production in the longer lateral wells, suggesting that lateral length is a primary factor responsible for the increased production.

To further examine how length, operator, and production are related, well production at 3, 6, 9, 12, and 18 months and cumulative production is contrasted against the actual lateral length in figure 15. The success of laterals longer than 9,000 ft is confirmed by this figure, and it again shows a disparity between operators. Note that wells with laterals greater than 10,000 ft do not display superior production than those between 9,001 ft and 10,000 ft. There appears to be no geologic reason why production does not continue to improve when drilling beyond 9,000 ft. Completion technology or practices may instead be the reason for this trend. The relationship between production and well length is also demonstrated on maps shown in figures 7-13.

Lateral orientation

The highest production in unconventional reservoirs is achieved if the horizontal leg of a well intersects the most permeable fractures within the rock. Although natural fractures in the subsurface may exist in a variety of directions, those oriented close to the present-day maximum horizontal stress direction, (S_{Hmax}) will be the best conduits for fluid flow. Induced fractures will also form parallel to $S_{Hmax,}$ so wells that are oriented perpendicular to S_{Hmax} will maximize production by encountering the highest number of hydrologically conductive natural and induced fractures.

The azimuth of the stress field can be determined directly through analysis of image logs, which show borehole breakouts and drilling-induced fractures that form at predictable orientations relative to S_{Hmax} (Zoback, 2010). Two image logs exist within the northern Denver Basin, both of which are approximately 20 miles northeast of the study area. The image log for the Jethro 44-19H well (API #49-015-20232) is the only legible log, and has been interpreted to indicate a minimum horizontal stress (S_{hmin}) direction of 30 degrees, or northeast-southwest, and an S_{Hmax} direction of northwest-southeast. The direction of S_{hmin} is subparallel to the basin axis near the location of this well in southern Goshen County (fig. 3).

In addition to north-south oriented wells intersecting the most natural fractures, these wells may also be remaining within a continuous facies of the Codell Sandstone. Because the Codell was deposited from the east or west, a more consistent composition would be probable in a north-south trend.

For this study, lateral well direction was calculated from the surface hole location to the bottom hole location for an overall well azimuth. All wells fell into a general north-south or east-west orientation, and in order to present similarly-oriented wells together, the well azimuths were corrected to an orientation within 70-200 degrees. For example, a well with an azimuth of 0 degrees was corrected to 180 degrees by adding 180, while a well with an orientation of 270 degrees was corrected to 90 degrees by subtracting 180.

Figure 16 shows 3, 6, 9, 12, and 18 months production and cumulative production compared to well lateral orientation. In all cases, wells oriented north-south outperform east-west wells. However, to better understand the influence of just lateral orientation on production, and remove the influence of lateral length, oil production was normalized per horizontal foot drilled and compared to drilling direction (fig. 17).

Monthly Oil Production by Lateral Length

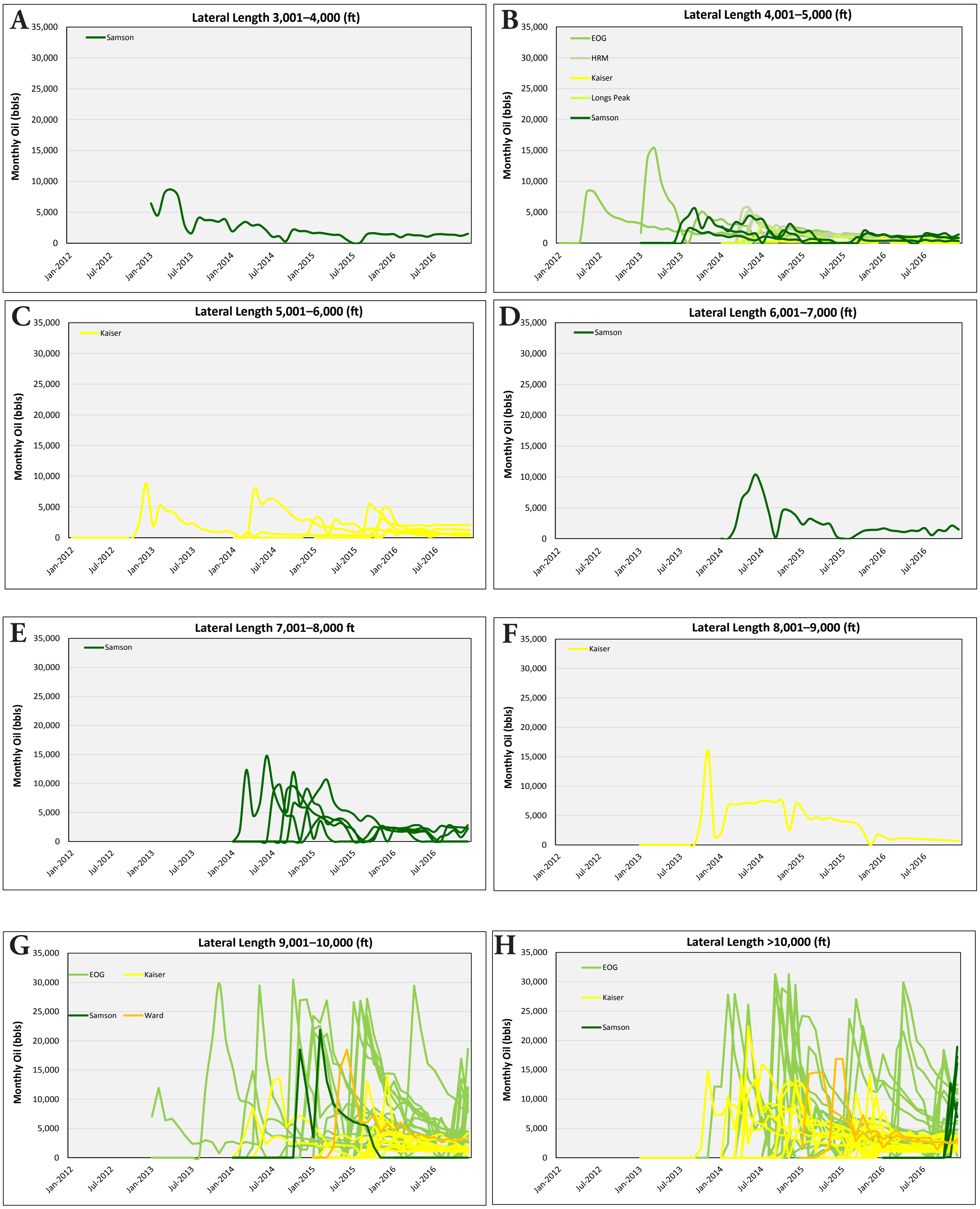


Figure 14. Monthly Codell Sandstone oil production from 2012 through 2016 for wells with lateral lengths of (A) 3,001–4,000 ft, (B) 4,001–5,000 ft, (C) 5,001–6,000 ft, (D) 6,001–7,000 ft, (E) 7,001–8,000 ft, (F) 8,001–9,000 ft, (G) 9,001–10,000 ft, and (H) greater than 10,000 ft. Wells are colored by operator.

First Months and Cumulative Oil Production vs. Lateral Length

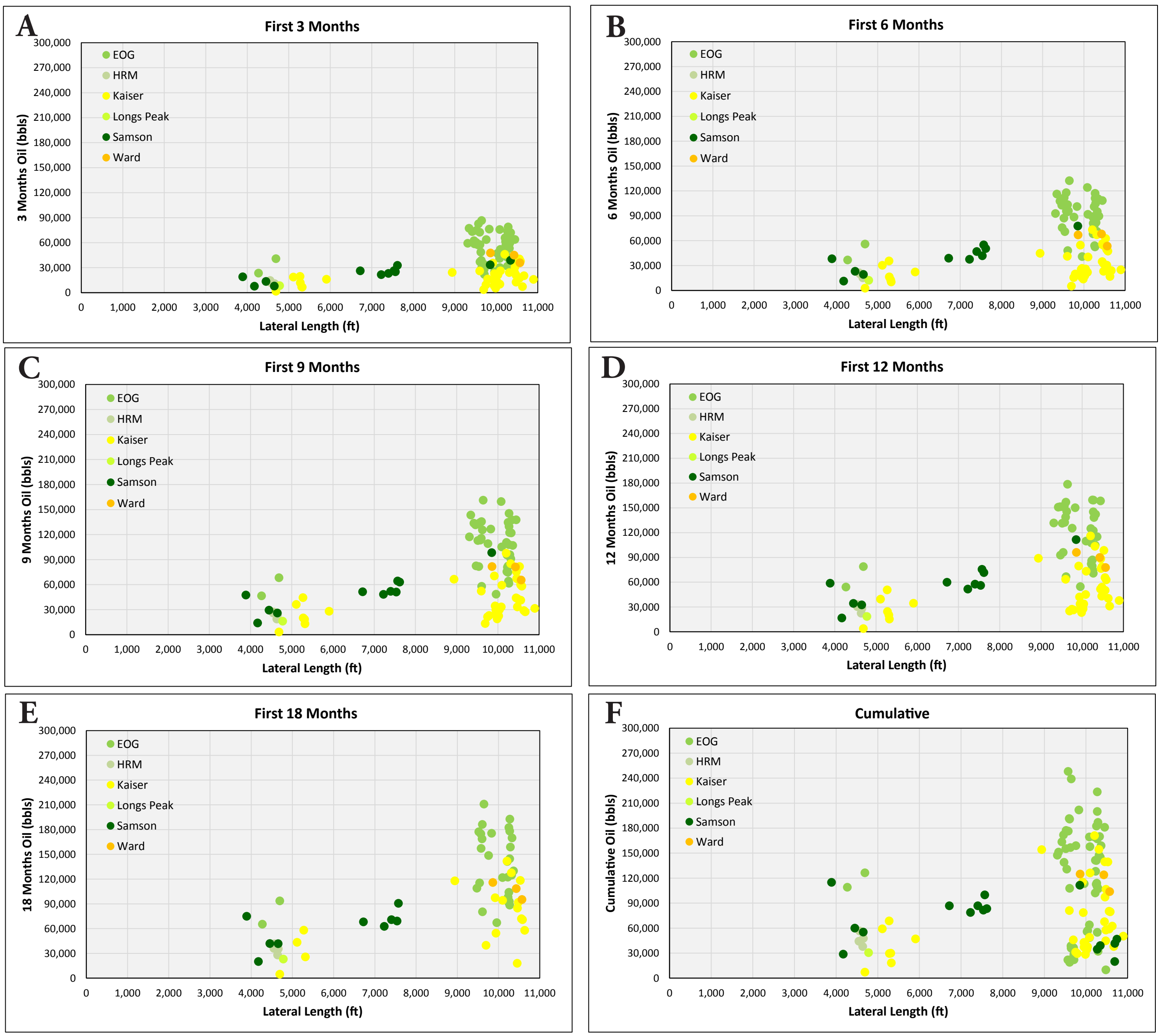


Figure 15. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production plotted as a function of lateral length. Wells are colored by operator.

First Months and Cumulative Oil Production vs. Lateral Orientation

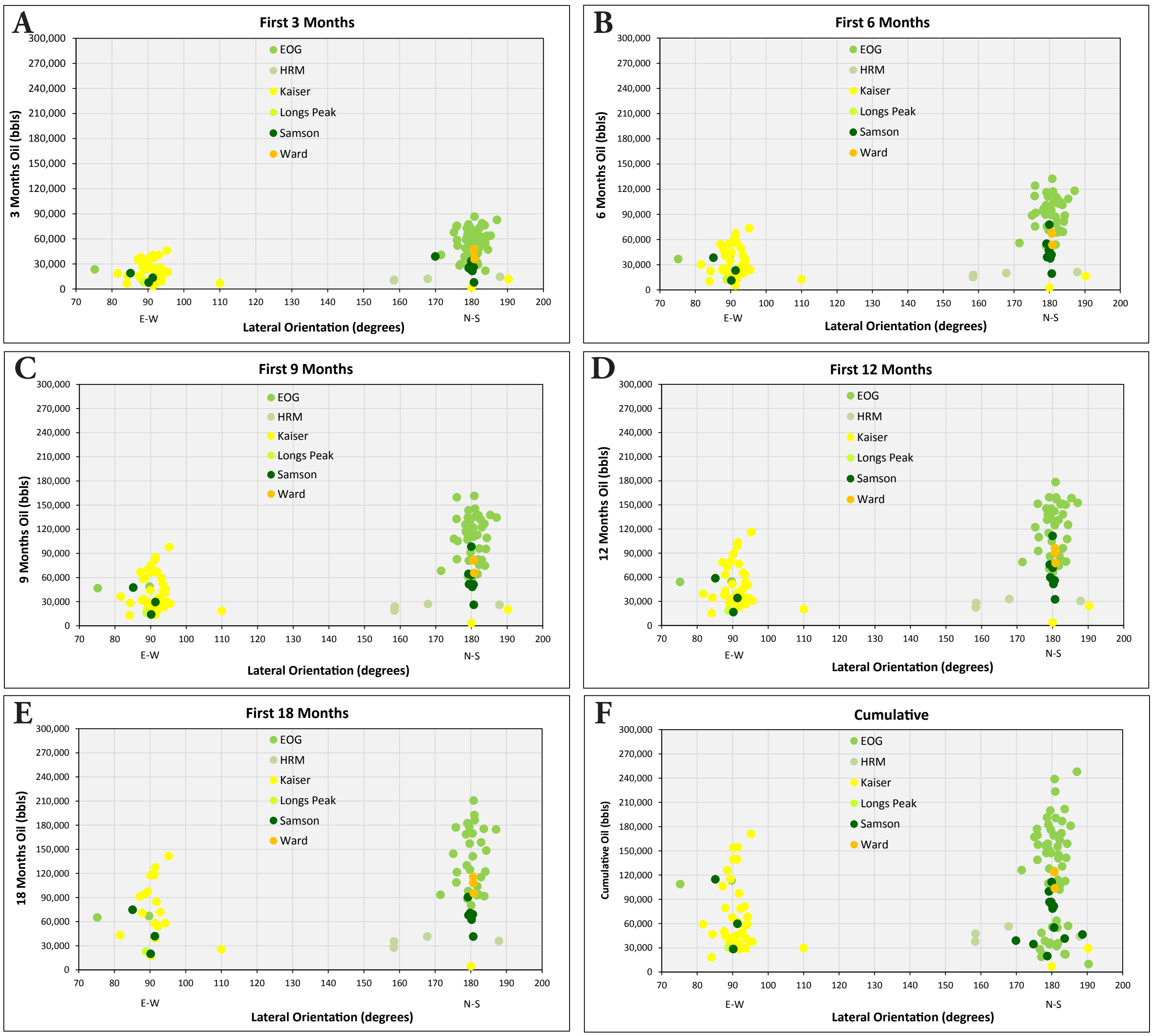


Figure 16. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production plotted as a function of lateral orientation. All lateral azimuths were normalized to 90° and 180° to show east-west and north-south trends, respectively. Wells are colored by operator.

First Months and Cumulative Oil Production per Lateral Length vs. Lateral Orientation

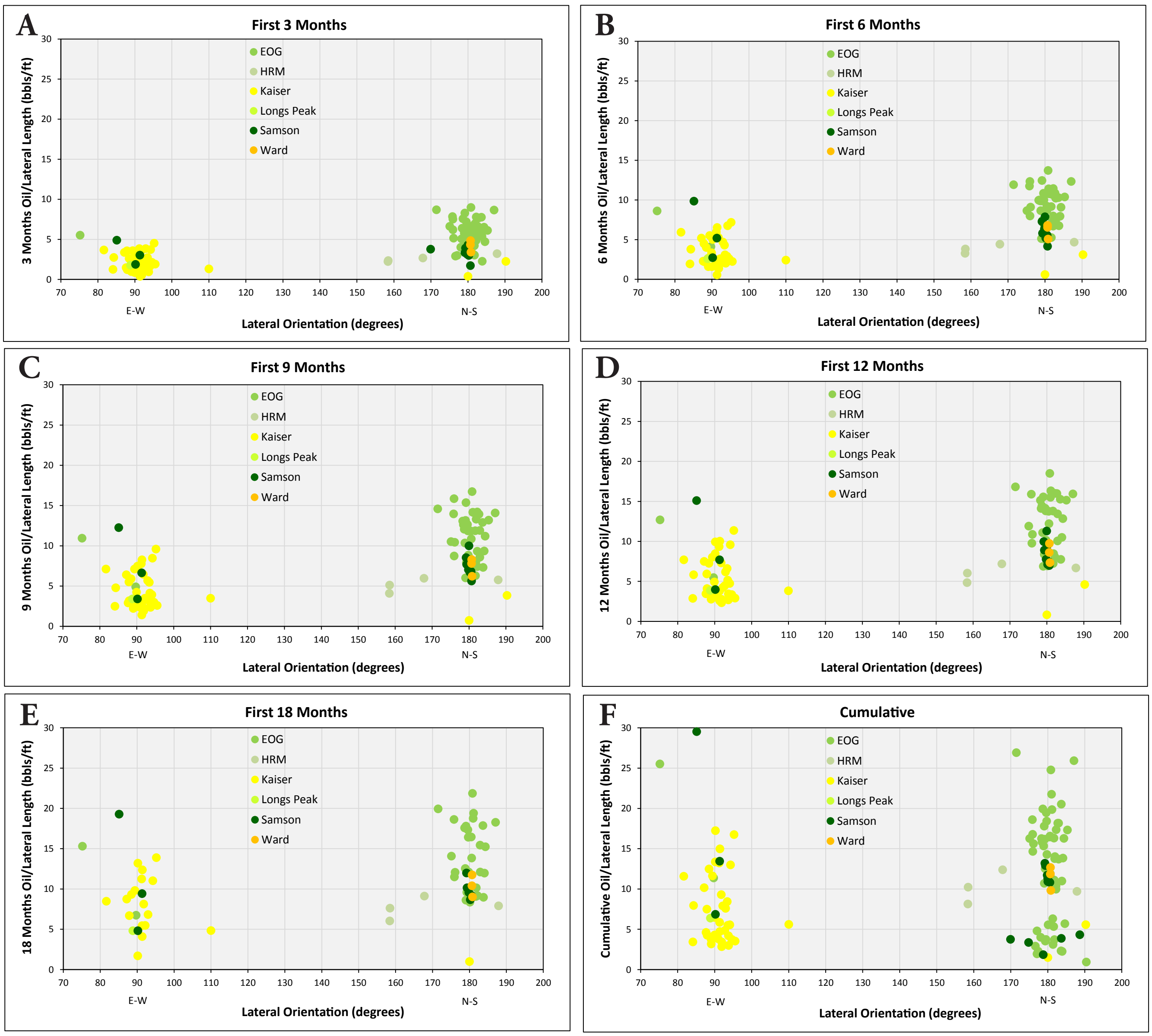


Figure 17. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production normalized by lateral length and plotted as a function of lateral orientation. All lateral azimuths were normalized to 90° and 180° to show east-west and north-south trends, respectively. Wells are colored by operator.

Figure 17 shows the same correspondence between high production and north-south orientation independent of lateral length, and this disparity becomes more pronounced with continued production. Two east-west wells appear to have high production per lateral foot (fig. 17), but they also have the shortest and third-shortest laterals (both less than 4,300 ft) and have been producing since at least 2013. These wells' extended production life but very short laterals artificially elevate their production per foot drilled.

Within the group of wells oriented north-south, two main populations of wells are evident. The division between the two populations lies at approximately 90,000 barrels (bbls) on fig. 16 and approximately 6.5 bbls/ft on fig. 17. This difference appears to be a function of lateral length and duration of production. The 44 wells with higher cumulative production all first produced between 2013 and 2016, have laterals longer than 9,000 ft, and an average production per lateral foot greater than 6.5 bbls/ft. Within the population of wells with lower production, 10 wells have less than 90,000 bbls cumulative production but more than 6.5 bbls/ft lateral length. These 10 wells all first produced in 2014 but have lateral lengths shorter than 9,000 ft, suggesting that although they have been producing long enough to increase the production per lateral foot, their short lateral length has negatively affected their cumulative production. Two wells with less than 90,000 bbls cumulative production and less than 6.5 bbls/ft have been producing for at least 12 and 18 months, respectively, but both have laterals shorter than 6,000 ft. The remaining 21 wells in this last category started production in 2016 and 2017 and have less than three months of production.

Figures 18A and B shows plots of production over time for wells oriented north-south versus east-west. These graphs indicate the higher rates of initial production in north-south wells, as well as a longer period of high production before the wells level off to production of 5,000 barrels per day or less. The correlation between production and well orientation is also represented in the maps shown in figures 7-13.

Completion

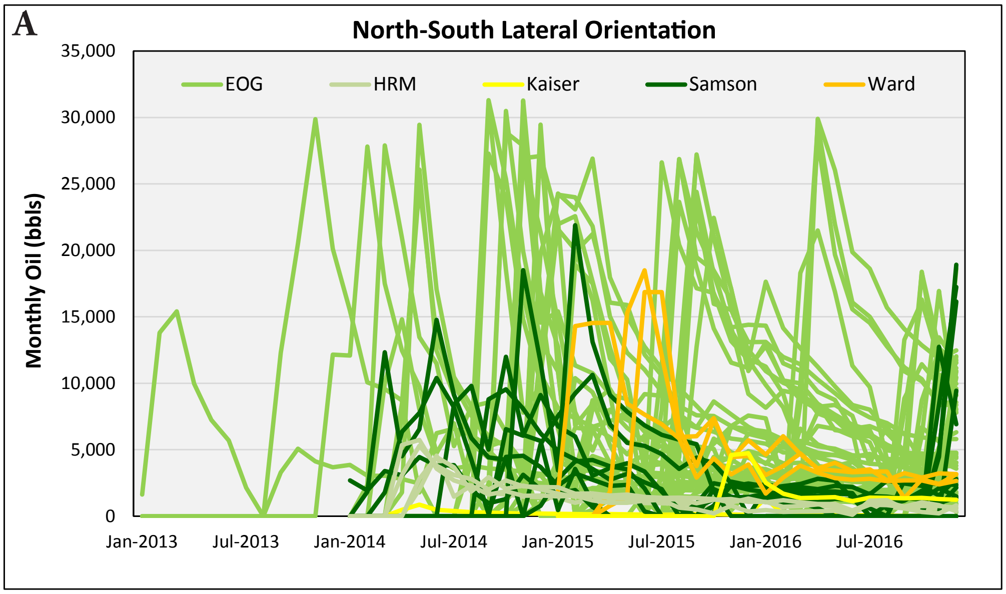
Although lateral orientation and length in part dictate how successful a well will be in the Codell Sandstone of the northern Denver Basin, unconventional reservoirs by definition have low porosity and/or permeability. Operators therefore need to hydraulically fracture the formation to increase the flow of oil into the wellbore. To determine what fracturing techniques correlate with successful wells in the study area, figures 19, 20, and 21 plot individual well production over progressive time intervals in relation to the number of frac stages, the amount of slurry, and the amount of proppant used.

Figure 19 shows oil production for 3, 6, 9, 12, and 18 months of production and cumulative production plotted against the number of frac stages in a well. Across all operators, production increases with increasing number of frac stages, and this difference becomes more pronounced over time. This trend does not, however, continue for wells with more than 45 frac stages.

A similar result was found in the plots shown in figure 20, which shows oil production for cumulative and first-months production plotted against volume of slurry in barrels. There is a point at approximately 200,000 barrels of slurry above which there is no increased production. Note in these plots, six wells with slurry amounts more than 600,000 barrels are not shown. These wells' extremely large slurry amounts did not yield increased production, and they were omitted to better evaluate the other 113 wells' completions.

The effect of proppant amount is examined in figure 21, which shows oil production for 3, 6, 9, 12, and 18 months and cumulative production plotted against total pounds of proppant used to frac the wells. From these plots, it appears that there is increased production up to 12.5 million pounds of proppant, but no improvement in production after that point.

Monthly Oil Production by Lateral Orientation



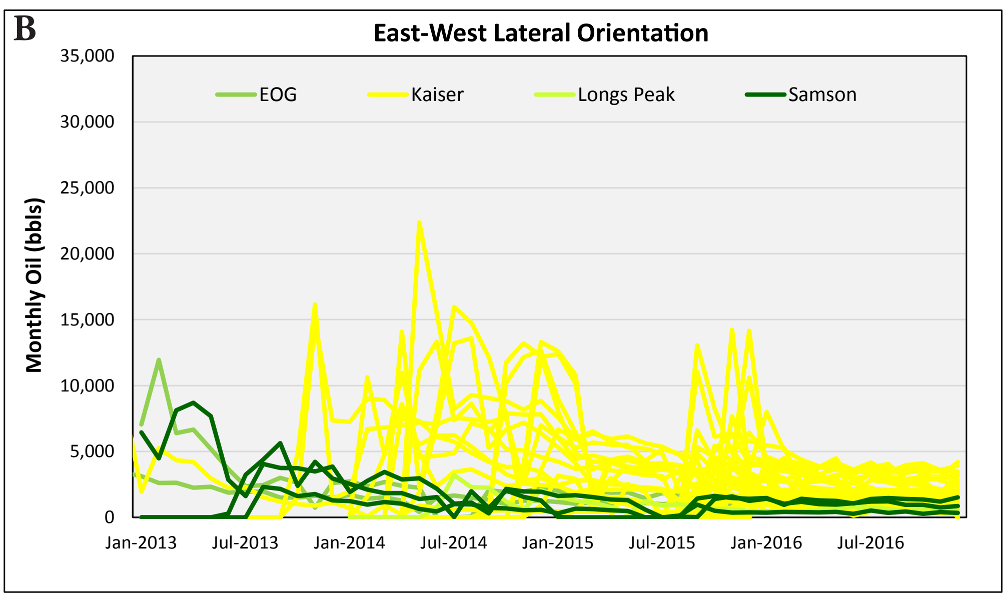


Figure 18. Monthly Codell Sandstone oil production from 2012 through 2016 for wells with laterals oriented (A) north-south and (B) east-west. Wells are colored by operator.

First Months and Cumulative Oil Production vs. Number of Frac Stages

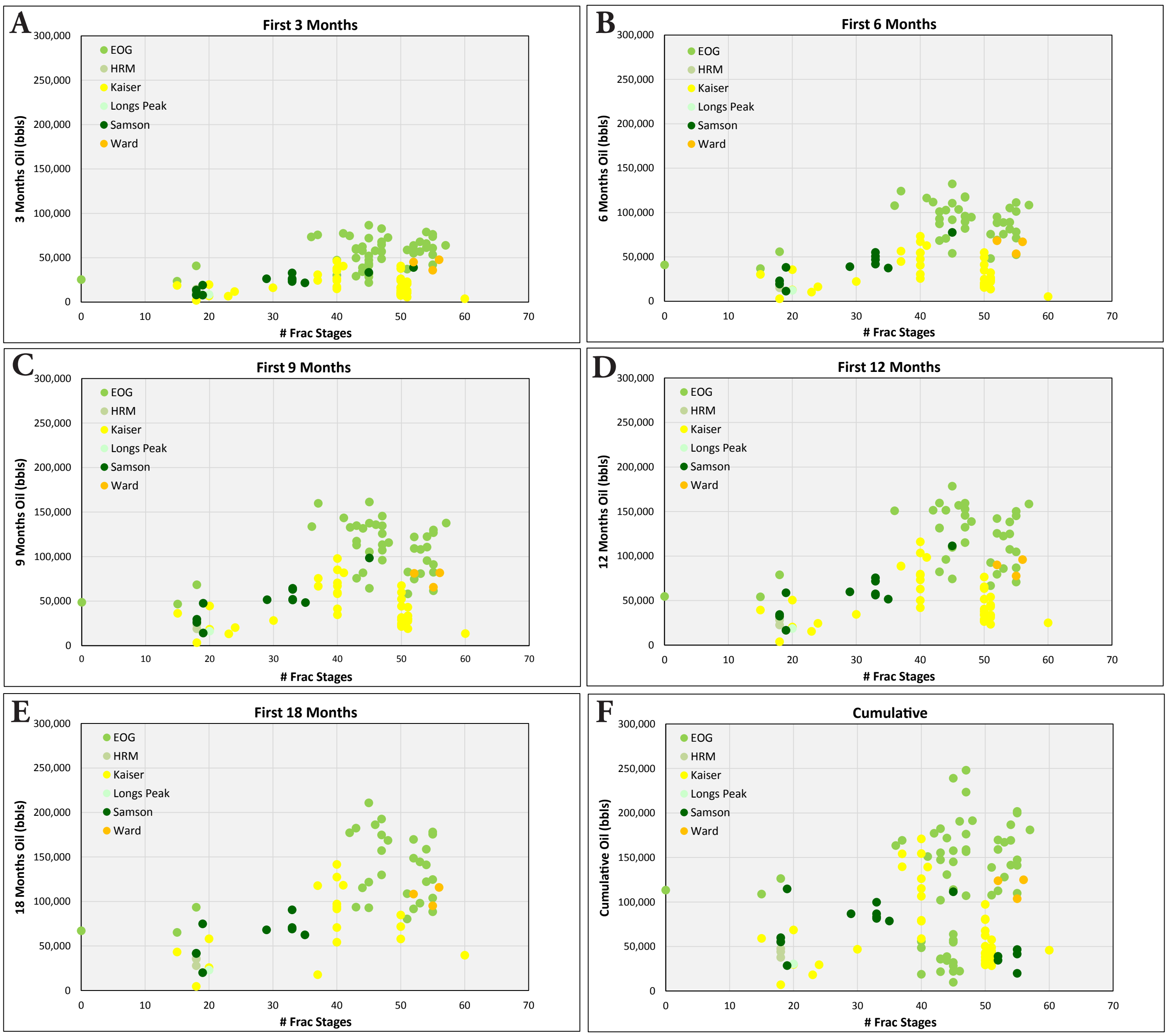


Figure 19. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production plotted as a function of the number of hydraulic fracturing (frac) stages used to complete each well. Wells are colored by operator.

First Months and Cumulative Oil Production vs. Slurry Volume

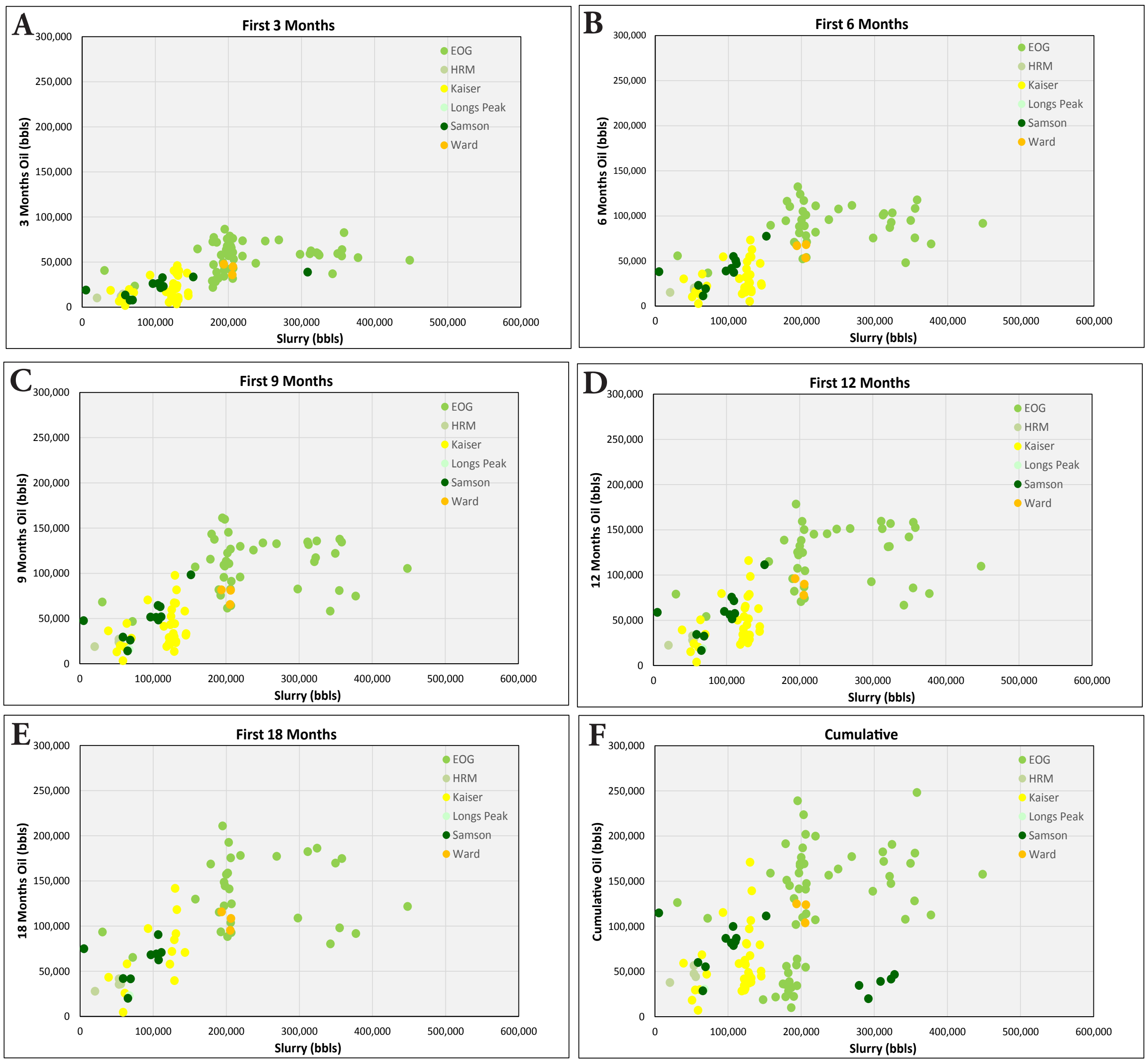


Figure 20. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production plotted as a function of the slurry volume used to complete each well. Six wells using greater than 600,000 bbls of slurry are not shown on this figure due to low production returns. Wells are colored by operator.

First Months and Cumulative Oil Production vs. Proppant Amount

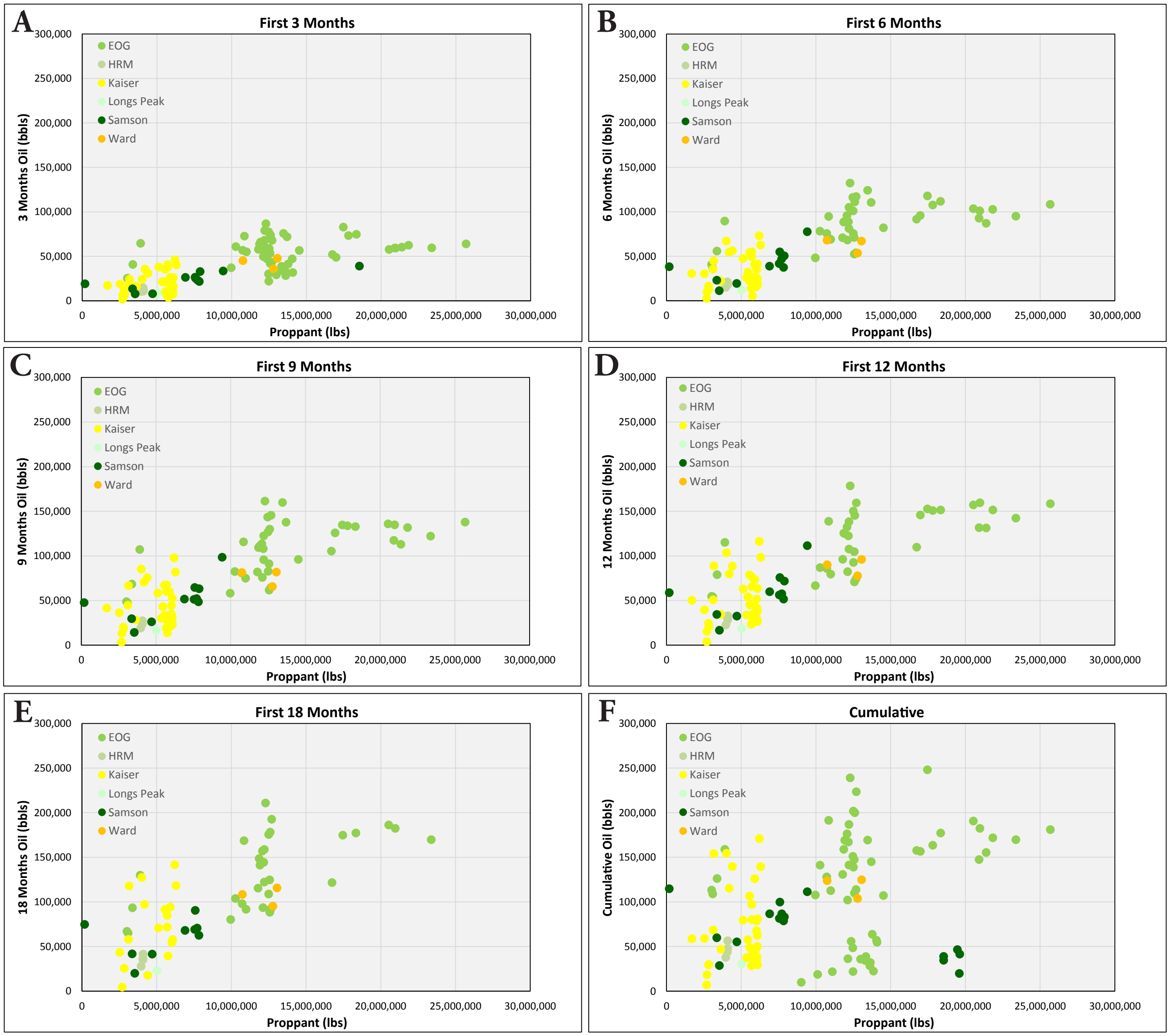


Figure 21. First (A) 3 months, (B) 6 months, (C) 9 months, (D) 12 months, and (E) 18 months of Codell Sandstone oil production, and (F) cumulative Codell Sandstone oil production plotted as a function of the amount of proppant used to complete each well. Wells are colored by operator.

These figures demonstrate that the most successful wells have more than 40 frac stages, at least 200,000 barrels of slurry, and more than 10 million pounds of proppant; these effective fracturing techniques are primarily used by one operator, and are probably interrelated. However, the results also indicate that with all three fracturing parameters, there reaches a point of diminishing returns. In general, more than 50 frac stages are not associated with higher production than 40 frac stages. Likewise, wells completed with slurry volumes greater than approximately 200,000 barrels and 12.5 million pounds of proppant do not correlate with better-producing wells. This suggests that there is an optimum range of hydraulic fracturing component amounts and fracturing design for wells completed in the northern Denver Basin Codell Sandstone.

SUMMARY

The spatial and graphical comparisons of Codell Sandstone production presented in this study highlight a consistent theme. Reservoir evaluations of the Codell using traditional depth, thickness, and structural trap methods fail to identify the most productive areas within the reservoir. The cross-sections, isopachs, and structure contour maps created by Anderson (2011) and Sterling and others (2016) do not explain the spatial production trends seen in figures 7-13. These figures indicate that the consistently highest-producing wells are currently clustered in the southern portion of the study area, often in the thinner sections of Codell Sandstone. Wells in this high-production southern area visually appear to have long laterals and are predominantly oriented north-south. If wells with long laterals and north-south orientations were drilled in the northern portion of the study area, well performance in this area may improve.

Cross-plots lend further support to the influence of lateral length and orientation on production. Wells drilled with laterals both longer than 9,000 ft and in a north-south orientation consistently outperform wells with shorter laterals and wells that are oriented east-west, even those of longer length. Long, north-south laterals intersect the most reservoir surface within a consistent depositional facies. This orientation may also encounter the most hydraulically conductive natural and induced fractures, which are subparallel to the direction of maximum horizontal stress. These wells' superior production is noticeable immediately after they begin producing and is sustained throughout their life.

Completion techniques that have resulted in the highest production were also examined in this report. Cross-plots comparing number of frac stages and amounts of proppant and slurry to early and cumulative production indicate that the best wells were completed with at least 40 frac stages, 200,000 bbls of slurry, and between 10 million and 12.5 million pounds of proppant. They also establish that for all three completion factors, there reaches a point of diminishing economic returns beyond which operators may not see a corresponding payoff in production.

In general, drilling and completion practices appear to dictate the success of Codell-producing wells in Laramie County, Wyoming. As operators expand into more areas of the basin, they will continue to test the hypothesis that where a Codell Sandstone well is drilled is less important than how it is drilled.

POTENTIAL FUTURE WORK

This study provides evidence that drilling and completion techniques strongly impact production from Codell Sandstone wells, but the influence of geologic and geomechanical properties on production is still unclear. A better understanding of the Codell Sandstone's brittleness and overpressure properties, along with research into the basin's stress orientation and natural fracture trends may help to explain and predict areas of highest production.

Because engineering methods and operational practices are an important factor in successfully developing unconventional reservoirs, and because the completions discussed in this study were limited to publicly available data, a more detailed analysis of completion and drilling techniques could provide insight into optimal practices. Identifying methods to extend production peaks past typical decline curves and improve wells' overall performance would be beneficial for industry, landowners and the state.

Cross-plots comparing well completion date to first production date and subsequent production performance may provide insight into the importance of production timing and infrastructure planning. This work could help operators identify the maximum time they can delay production before there is an effect on overall well performance.

Since the Codell Sandstone in Wyoming is a relatively new play, operators have learned and will continue to learn more effective completion techniques that optimize production. As future well and production data become available, this study can be expanded and updated, and the results will be less limited by the age of the wells.

Figure 22 displays the permitted, waiting-on-approval, and spudded Codell wells in Wyoming as of the WOGCC's March 2017 well header download. These wells provide a glimpse into the future plans of operators in the basin. New operators appear to be interested in the Codell as a viable oil reservoir, and current Codell operators will continue to drill wells in new areas. As operators expand their distinct drilling programs and completion practices across the basin, additional information will be added to this study's dataset to evaluate whether current spatial production trends are geology or completion driven.

The Wyoming State Geological Survey is in the process of performing similar analyses on additional unconventional plays in the Powder River Basin and northern Denver Basin.

ACKNOWLEDGMENTS

Tom Drean, director of the Wyoming State Geological Survey, had the foresight to suggest this project. His guidance and observations made this report possible.

We would also like to thank Ranie M. Lynds for her thorough, constructive edits, James R. Rodgers for his assistance in creating and refining figures, and Christina D. George for her editing and formatting expertise.

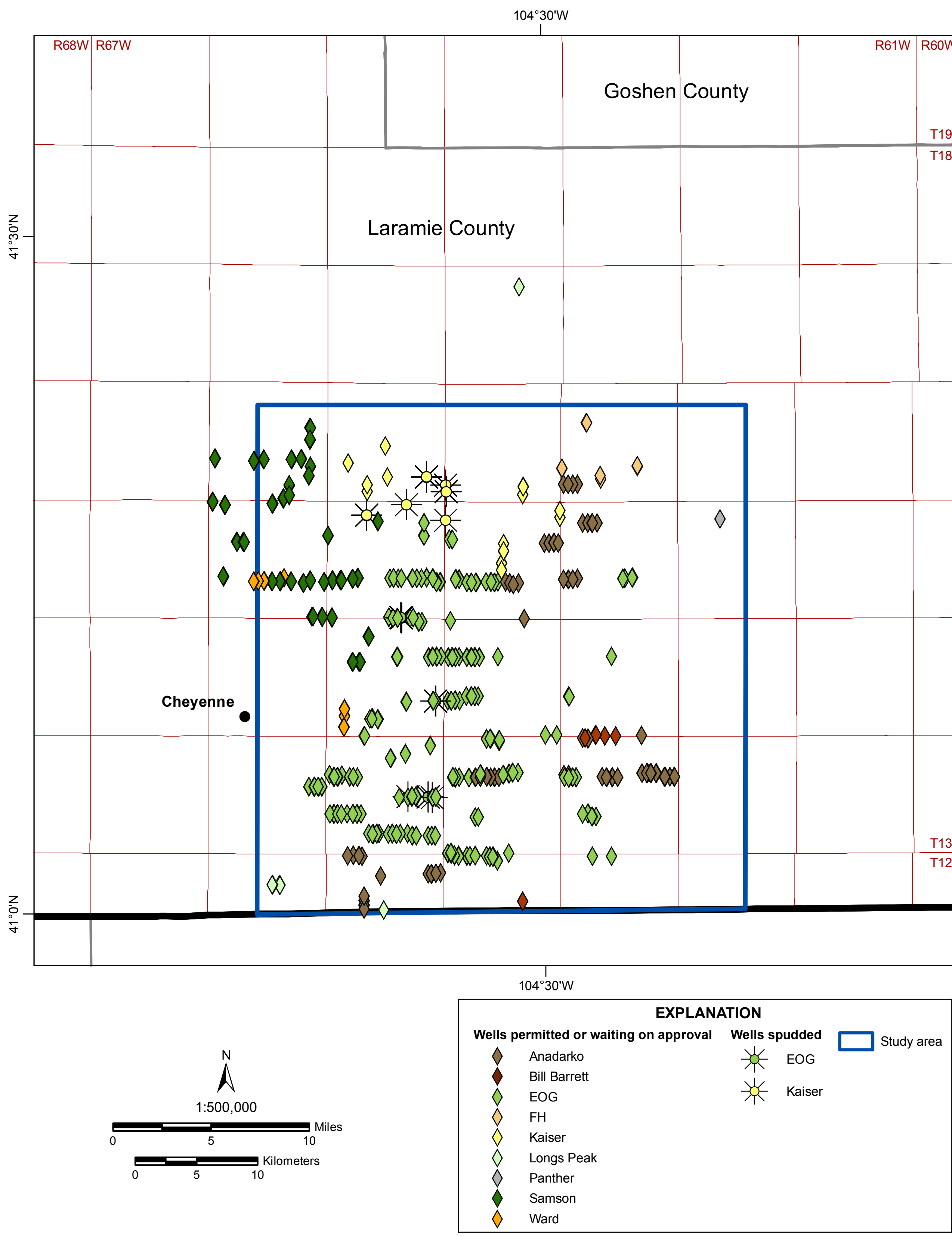


Figure 22. Map of possible future Codell Sandstone well locations. As of the WOGCC's March 2017 download, these wells have a permit-to-drill, waiting-on-approval, or spudded status, and will target the Codell Sandstone. Wells are colored by operator.

REFERENCES

Anderman, G.G., and Ackman, E.J., 1963, Structure of the Denver-Julesburg Basin and surrounding areas, *in* Bolyard, D.W., and Katich, P.J., eds., Geology of the northern Denver Basin and adjacent uplifts: Rocky Mountain Association of Geologists, p. 170–175.

Anderson, Adam, 2011, Stratigraphy and petroleum potential of the Codell Sandstone Member of the Carlile Shale, Northern Denver Basin, Southeastern Wyoming: Golden, Colorado School of Mines, M.S. thesis, 156 p.

Bass, N.W., 1926, Geologic investigations in western Kansas with special reference to oil and gas possibilities: Kansas State Geological Survey Bulletin 11, 96 p.

Birmingham, T.J., Lytle, D.M., and Sencebaugh, R.N., 2001, Enhanced recovery from a tight gas sand through hydraulic refracturing—Codell Formation, Wattenberg Field, Colorado, *in* Anderson, D.S., Robinson, J.W., Estes-Jackson, J.E., and Coalson, E.B., eds., Gas in the Rockies: Rocky Mountain Association of Geologists Special Publication, p. 101–116.

Burk, C.A., 1956, Stratigraphic summary of the Pre-Niobrara Formations of Wyoming, *in* Wyoming Stratigraphy—Subsurface Stratigraphy of the Pre-Niobrara Formations in Wyoming: Wyoming Geological Association, p. 91–97.

Clayton, J.L., and Swetland, P.J., 1980, Petroleum generation and migration in the Denver Basin: American Association of Petroleum Geologists Bulletin, v. 64, p. 1,613–1,624.

Higley, D.K., Pollastro, R.M., and Clayton, J.I., 1996, Denver Basin Province (039), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, one 200 MB CD–ROM.

Higley, D.K., and Cox, D.O., 2007, Oil and gas exploration and development along the front range in the Denver Basin of Colorado, Nebraska, and Wyoming: Petroleum systems and assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming—USGS Province, 39.

Kiteley, L.W., 1978, Stratigraphic sections of Cretaceous Rocks of the northern Denver Basin, northeastern Colorado and southeastern Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart 78.

Krutak, P.R., 1970, Origin and depositional environment of the Codell Sandstone Member of the Carlile Shale (Upper Cretaceous) southeastern Colorado: The Mountain Geologist, v. 7, no. 3, p. 185–204.

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000. (Re-released 2014, Wyoming State Geological Survey.)

Martin, C.A., 1965, Denver Basin: Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1,908–1,925.

Merewether, E.A., and Cobban, W.A., 1973, Stratigraphic sections of the Upper Cretaceous Frontier Formation near Casper and Douglas, Wyoming: Wyoming Geological Association Earth Science Bulletin, v. 6, no. 4, p. 38–39.

Merewether, E.A., and Cobban, W.A., 1986, Biostratigraphic units and tectonism in the Mid-Cretaceous Foreland of Wyoming, Colorado, and adjoining areas: Part III, Middle Rocky Mountains.

Merewether, E.A., Cobban, W.A., and Cavanaugh, E.T., 1979, Frontier Formation and equivalent rocks in eastern Wyoming: The Mountain Geologist, v. 16, no. 3, p. 67–101.

Merewether, E.A., Cobban, W.A., and Obradovich, J.D., 2007, Regional disconformities in Turonian and Coniacian (Upper Cretaceous) strata in Colorado, Wyoming, and adjoining states—Biochronological evidence: Rocky Mountain Geology, v. 42, no.2, p. 95–122.

Merewether, E.A., Cobban, W.A., and Obradovich, J.D., 2011, Biostratigraphic data from Upper Cretaceous Formations—Eastern Wyoming, central Colorado, and northeastern New Mexico: U.S. Geological Survey Scientific Investigations Map 3175 (pamphlet), 2 sheets, 10 p.

Nolte, C.J., 1963, Potential stratigraphic accumulation of oil and gas in the Upper Cretaceous of the Denver Basin, *in* Geology of northern Denver Basin and adjacent uplifts: Rocky Mountain Association of Geologists 14th annual field conference, Guidebook, p. 156–161.

Rice, D.D., 1984, Relation of hydrocarbon occurrence to thermal maturity of organic matter in the Upper Cretaceous Niobrara Formation, Eastern Denver Basin—Evidence of biogenic versus thermogenic origin of hydrocarbons, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain area: Rocky Mountain Association of Geologists Guidebook, p. 365–368.

Rice, D.D., and Threlkeld, C.N., 1983, Character and origin of natural gas from Upper Cretaceous Codell Sandstone, Denver Basin, Colorado: Mid-Cretaceous Codell Sandstone Member of Carlile Shale eastern Colorado (Spring Field Trip Guidebook), Rocky Mountain Section SEPM (Society for Sedimentary Geology).

Smith, K.H., 2015, Codell Sandstone, DJ Basin: AAPG Annual Convention and Exhibition: Short Course 17, Tight Oil Sandstone Reservoirs, Wyoming and Colorado: Denver Core Workshop, Denver, Colo., June 4, 2015.

Smith, K.H., Bottjer, R.J., Sterling, R.H., Nowak, H.C. and Wheat, D.R., 2014, Reservoir Characteristics of the Codell Sandstone Tight Oil Play, Northern DJ Basin, Wyoming and Colorado: Extension of Wattenberg into the Oil Window: AAPG Rocky Mountain Section Meeting, Denver, Colo., July 20–22, 2014.

Smith, K.H., Bottjer, R.J., Sterling, R.H., Nowak, H.C. and Berkman, T.A., 2015, Codell Sandstone, northern DJ Basin, Wyoming and Colorado: Reservoir characteristics in a tight oil play: AAPG Annual Convention and Exhibition, Denver, Colo., May 31–June 3, 2015.

Sonnenberg, S.A., 1985, Northwest Denver Basin/southeast Hartville uplift, *in* Gries, R.R., and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 213–217.

Sonnenberg, S.A., 1987, Tectonic, sedimentary, and seismic models for D sandstone, Zenith Field area, Denver Basin, Colorado: Association of Petroleum Geologists Bulletin, v. 71, no. 11, p. 1,366–1,377.

Sonnenberg, S.A., 2014, The Codell Sandstone resource play of the Northern Denver Basin: Unconventional Resources Technology Conference, Denver, Colo., August 25–27, 2014: p. 2,869–2,879.

Sonnenberg, S.A., 2015, Geologic factors controlling production in the Codell Sandstone, Wattenberg field, Colorado: Unconventional Resources Technology Conference, San Antonio, Texas, July 20–22, 2015, p. 2,843–2,859.

Sterling, R.H., Bottjer, R.J., and Smith, K.H., 2015, Codell Sandstone, A review of the northern DJ Basin oil resource play, Laramie County, Wyoming, and Weld County, Colorado: AAPG Annual Convention and Exhibition, Denver, Colo., May 31–June 3, 2015.

Sterling, R.H., Bottjer, R.J., and Smith, K.H., 2016, Codell Sandstone, A review of the northern DJ Basin oil resource play, Laramie County, Wyoming, and Weld County, Colorado: Unconventional Resources Technology Conference, San Antonio, Texas, August 1–3, 2016, p. 3,146–3,154.

Towler B.F., and Gao T.P., 2011, Silo field Niobrara Reservoir modeling (presentation): University of Wyoming Enhanced Oil Recovery Institute, January 2011, 65 p.

Weimer, R.J., 1984, Relation of unconformities, tectonics, and sea-level changes, Cretaceous of western interior, U.S.A., *in* Schlee, J.S., ed., Interregional unconformities and hydrocarbon accumulations: American Association of Petroleum Geologists Memoir 36, p. 7–35.

Weimer, R.J., and Sonnenberg, S.A., 1983, Codell Sandstone, new exploration play, Denver Basin, *in* Spring Field Trip Guidebook, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 26–48.

WOGCC, 2017, Wyoming Oil and Gas Conservation Commission, data download, accessed March 2017, at http://wogcc.state.wy.us/legacywogcce.cfm.

Zoback, M.D., 2010, Reservoir Geomechanics: New York, N.Y., Cambridge University Press, 449 p.