Influences on Oil and Natural Gas Production from the Wall Creek and Turner Sandstone Reservoirs, Powder River Basin, Wyoming

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Cover photo: Photograph of Wall Creek Member of the Frontier Formation, near Kaycee, Wyoming. (Photo credit: Rebekah Rhodes, University of Wyoming Department of Geology and Geophysics)

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ABSTRACT

The Upper Cretaceous Wall Creek Sandstone Member of the Frontier Formation and the Turner Sandy Member of the Carlile Shale are emerging as one the most prolific unconventional plays in the Powder River Basin of Wyoming. Between January 2017 and July 2018, 21.7 million barrels of oil and 84.3 million cubic feet of natural gas were produced from horizontal Wall Creek or Turner wells. This production accounted for 33 percent of all oil and 23 percent of all natural gas produced from the basin during this time period. Since January 2017, 17 percent of all approved permits to drill in Wyoming have been for wells targeting the Powder River Basin Wall Creek and Turner reservoirs.

This study evaluates horizontal drilling and completion practices, in addition to reservoir geology, to determine if these factors impact production from the Wall Creek and Turner reservoirs. Wall Creek-Turner oil and gas production is graphically compared to the producing interval lengths and lateral orientations of horizontal wells, completion techniques such as hydraulic fracturing (frac) stages, slurry and proppant volumes, and operator-specific trends over time. Interpolated surfaces and contours are used to spatially compare production trends to reservoir characteristics, including formation depth, thickness, pressure, temperature, regional structural features, and hydrocarbon compositions such as crude oil American Petroleum Institute (API) gravity, gas-oil ratios, and gas-fraction ratios. The graphical, spatial, and statistical comparisons of these variables suggest that hydrocarbon production from the complex Wall Creek-Turner reservoir system is more influenced by geology than by horizontal well completion techniques.

An interactive online map accompanies this investigation, allowing users to view datasets in greater detail and better visualize how the geology and reservoir attributes of the Wall Creek and Turner vary spatially. Interpreting the influence of geologic attributes on production is further facilitated by the ability to visually superimpose multiple datasets. This online map is available at the Wyoming State Geological Survey (WSGS) publications webpage (https://www.wsgs.wyo.gov/pubs-maps/publication-search).

INTRODUCTION

Scope of Investigation

Since the 1908 discovery of the Salt Creek field, the Powder River Basin (PRB) has been a prolific hydrocarbon-producing basin, averaging 43 percent and 15 percent of all Wyoming oil and natural gas production, respectively (Wyoming Oil and Gas Conservation Commission [WOGCC], 2018). Oil and gas were historically produced from the basin's Paleozoic formations and conventional structural and stratigraphic traps. However, current exploration and development efforts are focused on stacked, unconventional Upper Cretaceous tight-sand and shale reservoirs, including the Wall Creek Member of the Frontier Formation (Wall Creek) and the coeval Turner Sandy Member (Turner) of the Carlile Shale.

Because the Wall Creek and Turner have become primary development targets, it is important to understand what influences oil and gas production from these reservoirs. Influencing factors generally fall into one of two categories: how wells are completed or reservoir geology. This study therefore compiles and graphically evaluates Wall Creek and Turner horizontal well completion techniques in relation to each well's oil and gas production. Spatial and statistical analyses of reservoir petrophysical attributes identify additional influences on production and characteristics that distinguish the Wall Creek reservoir from the Turner reservoir.

Geologic Setting

The Powder River Basin extends from southeastern Montana into northeastern Wyoming, with more than 16,000 square miles (mi^2) of the basin located in Wyoming. Laramide-age deformation formed the PRB's current geometry and the uplifts that flank the basin, including the Bighorn Mountains, Casper Arch, Laramie Mountains, Hartville Uplift, and Black Hills in Wyoming (fig. 1). The basin's axis trends generally northwest–southeast (NW–SE) and is located near the western margin, creating an asymmetric basin geometry with steeply dipping strata west of the axis and shallow to sub-horizontal dips to the east (fig. 2). More than 25,000 feet (ft) of structural relief offsets the Precambrian basement along the basin's western edge (Blackstone, 1981; Stone, 2003).

The PRB is a deep foreland basin, with nearly 18,000 ft of Cambrian- to Eocene-age sediments (Dolton and Fox, 1996; Anna, 2010). Paleozoic strata were deposited as part of the western North American passive margin, represented by interbedded sandstones and carbonates (Boyd, 1993; Snoke, 1993). Non-marine sediments were deposited during the Triassic and Jurassic from western continental accretion processes (Picard, 1993). The Sevier orogeny, characterized by thin-skinned faulting in what is now western Wyoming, began toward the end of the Early Cretaceous (Royse, 1993). Subsidence from crustal loading during the Sevier orogeny formed a foreland basin in central and eastern Wyoming, which was subsequently flooded by the epicontinental Western Interior Seaway (WIS; Steidtmann, 1993). Wyoming's Upper Cretaceous reservoirs were deposited during the numerous transgres-

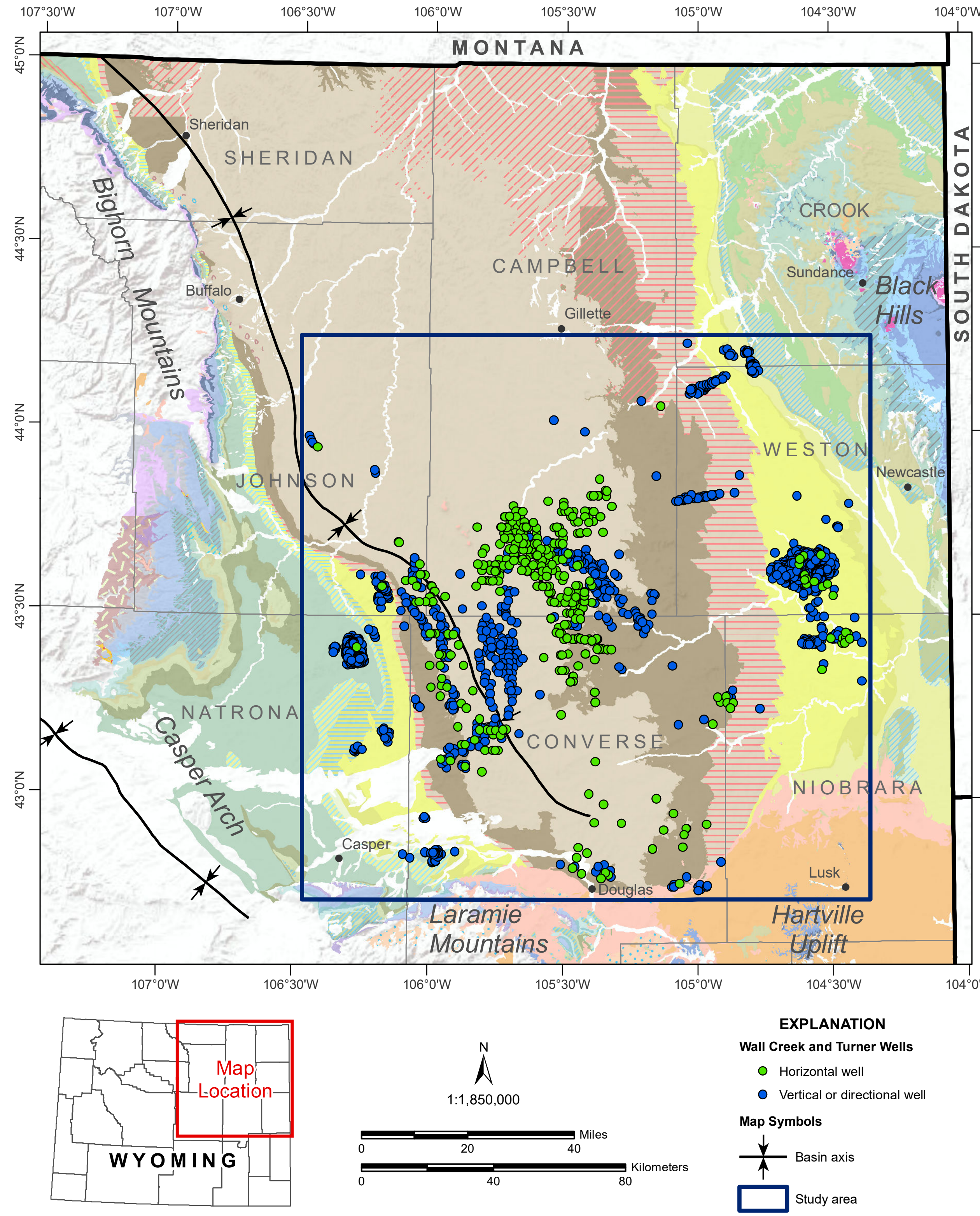

Figure 1. Powder River Basin bedrock geology (Love and Christiansen, 1985) and study area overview map. Geologic unit ages and colors follow Love and Christiansen (1985): Paleogene—browns, oranges, and pinks; Mesozoic—yellows and greens; Paleozoic—blues and purples. The basin is bounded by Precambrian-cored uplifts. Horizontal, vertical, and directional wells producing from the Wall Creek and Turner define the study area.

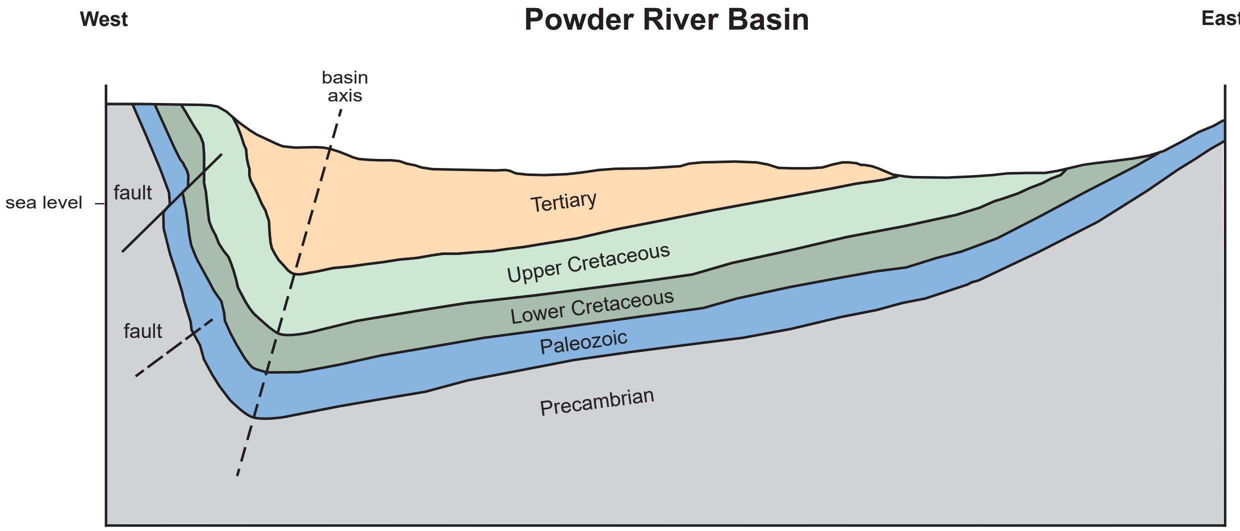

Figure 2. Schematic west–east Powder River Basin cross section. The axis of the Powder River Basin is located near the western basin margin and separates steeply dipping strata in the west from shallower-dipping strata to the east. Modified from Anna (2010).

sions and regressions of the WIS and were later separated by Laramide orogeny basement-involved uplifts during the Campanian through Eocene (Curry, 1971; Brown, 1993; Steidtmann, 1993). Cretaceous and Paleogene outcrops dominate the central portion of the PRB, while high-angle Paleozoic, Jurassic, and Triassic strata are exposed on the basin's edges near the Black Hills and Bighorn Mountains (fig. 1).

STRATIGRAPHY

Although numerous publications have described the Frontier and Carlile formations, this section focuses only on Wall Creek- (and its nomenclature equivalents of "First Frontier" and "First Wall Creek") and Turner-specific studies in the Powder River Basin.

Age

Fossil assemblage studies by Cobban and Reeside (1952), Haun (1958), and Robinson and others (1964) were the first to specify a Turonian age for the Wall Creek and Turner sandstones. Subsequent investigations by E.A. Merewether refined the strata's chronostratigraphy and determined that biostratigraphic zones *Scaphites warreni* to *Prionocyclus germari* constrain the deposition of both the Wall Creek and Turner to the late Turonian, approximately 90.05–89.3 million years ago (Ma; Merewether and others, 1979; Merewether, 1980; Merewether and Cobban, 1986a; Merewether, 1996; Merewether and others, 2007; Merewether and others, 2011). Regional coeval formations include the Juana Lopez Member of the Carlile Shale in southeastern Colorado and northeastern New Mexico (Merewether and others, 2007, 2011) and the Codell Sandstone Member of the Carlile Shale in Kansas, northern Colorado, and southeastern Wyoming, although Merewether and others (2007, 2011) indicate the Codell Sandstone may actually be slightly older than the Wall Creek and Turner.

Formation Descriptions

Wall Creek

The Wall Creek Sandstone represents the uppermost sandstone member in the Upper Cretaceous Frontier Formation (fig. 3). It is located in the west–southwestern portion of the PRB, and has a conformable, interfingering upper contact with the basal members of the Cody Shale (Sage Breaks and Niobrara members). Where present, the thin Emigrant Gap Member of the Frontier Formation forms the unconformable lower contact of the Wall Creek. Where the Emigrant Gap Member is absent, the basal Belle Fourche Member of the Frontier Formation defines the base of the Wall Creek Sandstone.

Wegemann's (1911) study of the Salt Creek oil field was the first to use the term "Wall Creek sandstone lentil." Subsequent efforts to subdivide the PRB Frontier Formation are varied, complicated, and inconsistent. Proposed terminology typically used numerically ordered, informally named Wall Creek and Frontier sands (Towse, 1952; Goodell, 1962; Barlow and Haun, 1966; WOGCC, 2018) or laterally continuous bentonite beds (Towse, 1952) and sandstones (Merewether and others, 1979) to define the units.

Older stratigraphic descriptions and petrologic studies have been published in varying detail for the Wall Creek Sandstone by Downs (1949), Cobban and Reeside (1952), Towse (1952), Hose (1955), Faulkner (1956), Haun (1958), Goodell (1962), Barlow and Haun (1966), Merewether and others (1979), Tillman and Almon (1979), Merewether (1980), Winn and others (1983), Merewether and Cobban (1986b), Winn (1986, 1991), and Merewether (1996). More recent stratigraphic studies of the Wall Creek focus on refining its facies heterogeneity (Lee and others, 2005, 2007; Sadeque, 2006; Gani and Bhattacharya, 2007; Melick, 2013; Fluckiger and others, 2015; Gustason, 2015; Rhodes, 2015; La Fontaine, 2018).

Authors often further subdivide the Turner for correlation and lithological description purposes. It has been delineated into upper, middle, and lower sand lithologies (Weimer and Flexer, 1985), in addition to upper and lower Turner sand intervals (Rice and Gaskill, 1988), units (Charoen-Pakdi and Fox, 1989), and stratigraphic traps (Rice and Keighin, 1989). Heger (2016) references an upper and lower Turner with 3 flooding surfaces and 7 facies groups with 15 subfacies. Melick (2013) divides the combined Wall Creek-Turner reservoir into four 4th-order, basin-scale transgressive-regressive stratigraphic cycles delineated by ammonite biozones, each representing approximately 400,000 years and 100–300 ft of deposition.

Outcrop and core descriptions indicate the sand-rich Wall Creek is composed of several coarsening-upward packages of interbedded shales, siltstones, and sandstones (Merewether and others, 1979; Tillman and Almon, 1979; Winn, 1986; Sadeque, 2006; Rhodes, 2015). Pebble conglomerates occur both at the base of the Wall Creek and near the top of several coarsening-upward sequences (Merewether and others, 1979; Rhodes, 2015). Laminations and rippled cross-stratified bedding transition upward in each sequence to trough and tabular cross-bedding (Merewether and others, 1979; Rhodes, 2015). Bioturbation from *Cruziana* and *Skolithos* ichnofacies is prevalent throughout the Wall Creek, and in some sections completely eliminates the bedding structures (Rhodes, 2015).

Turner

The Upper Cretaceous Carlile Shale's upper sandstone interval is interchangeably called either the "Turner Sandy Member" (first termed by Rubey, 1930) or "Turner Sandstone" (fig. 3). Found in the east–southeastern half of the PRB, the Turner Sandstone is conformably overlain by the Carlile Shale's uppermost Sage Breaks Member. The base of the Turner is often defined by an unconformable contact with the Pool Creek Member of the Carlile Shale. In areas where the Pool Creek Member does not exist, the Turner unconformably rests on the carbonate-rich Greenhorn Formation. Both the Wall Creek and Turner sandstones' basal contacts have been interpreted as disconformities representing an extensive regional hiatus that lasted approximately 2–2.42 million years (Merewether and others, 1979; Merewether, 1980; Heger, 2016).

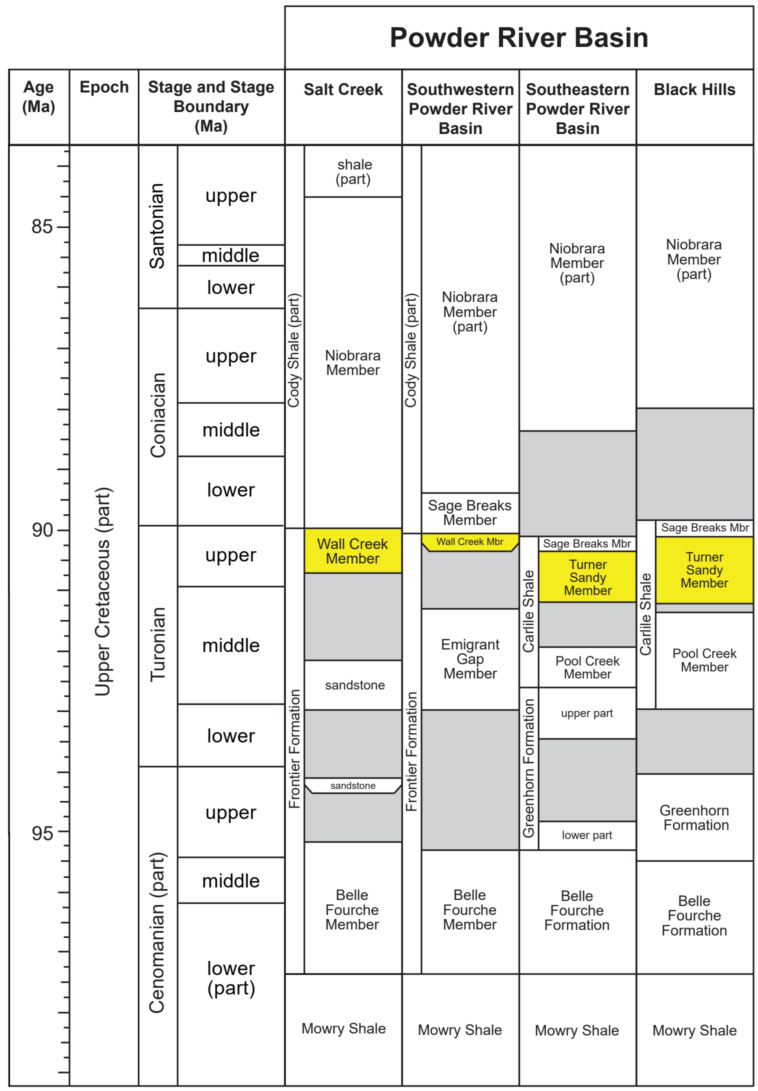

Figure 3. Stratigraphic column of Powder River Basin Cenomanian through Santonian strata. The Wall Creek Member of the Frontier Formation and the Turner Sandy Member of the Carlile Shale, highlighted in yellow, are chronologically equivalent. Gray spaces indicate missing or condensed section. Member is abbreviated Mbr. Modified from Lynds and Slattery (2017).

Turner stratigraphy and petrology has been previously described by Cobban (1952), Hose (1955), Faulkner (1956), Haun (1958), Robinson and others (1964), Merewether and others (1979), Merewether (1980), Weimer and Flexer (1985), Charoen-Pakdi and Fox (1989), Rice and Keighin (1989), and Merewether (1996). Like the Wall Creek, more recent studies focus on facies delineation of the Turner (Melick, 2013; Gustason, 2015; Heger, 2016).

The base of the Turner is described both in outcrop and core as a fine- to medium-grained, sub-horizontally laminated and cross-bedded sandstone with scour and fill features, and a phosphatic, chert, and quartz pebble lag containing shark teeth (Rubey, 1930; Cobban, 1952; Weimer and Flexer, 1985; Merewether, 1996). This basal facies grades upward into a sequence of very fine to fine-grained sandstone interbedded with siltstones and mudstones displaying hummocky cross-stratification, ripples, and an upward increase in bioturbation intensity (Weimer and Flexer, 1985; Rice and Keighin, 1989; Bottjer and others, 2017).

Depositional Environment

The Wall Creek and Turner sandstones appear to record a transition from nearshore to distal environments on the western margin of the WIS during a period of global sea level rise but local relative regression (Kauffman, 1977; Merewether and Cobban, 1986a, b; Roberts and Kirschbaum, 1995; Rhodes, 2015). Bartram (1932) was one of the first to suggest a deltaic depositional environment for the Wall Creek. This depositional interpretation, and that of the Turner, has continued to be refined by numerous subsequent studies, including those by Goodell (1962), Brenner (1979), Merewether and others (1979), Merewether (1980), Merewether and Claypool (1980), Winn and others (1983), Weimer and Flexer (1985), Merewether and Cobban (1986b), Winn (1986), Charoen-Pakdi and Fox (1989), Rice and Keighin (1989), Winn (1991), Merewether (1996), Lee and others (2005, 2007), Sadeque (2006), Gani and Bhattacharya (2007), Melick (2013), Rhodes (2015), and Heger (2016).

Strata exposed in the Sevier fold-and-thrust belt in Idaho and western Wyoming are considered the most likely sediment source for both the Wall Creek and Turner sandstones (Goodell, 1962; Winn, 1991; Melick, 2013; Rhodes, 2015), although Winn (1991) suggests that the Wall Creek may also have had minor input from the older Emigrant Gap and Belle Fourche members of the Frontier Formation. Sediment was transported down-dip from the Sevier uplifts by fluvial systems that drained into the western margin of the WIS. Winn (1991) places a delta-strandplain source near the present-day Bighorn Mountains. Merewether and others (1979) narrow the position of the delta to between the towns of Ervay and Douglas, Wyoming, while Rhodes (2015) suggests a more northerly location near Kaycee, Wyoming.

Merewether and others (1979) propose the PRB's sediment transport direction during the Turonian was initially toward the north-northeast. However, cross-bedding within the sandstones document a southern mean paleocurrent vector. Southwestern and southeastern currents are evident in Wall Creek and Turner bedding, respectively, and are interpreted as storm reworking of the original deposits (Towse, 1952; Cavanaugh, 1976; Merewether and others, 1979; Winn, 1991; Merewether, 1996; Gustason, 2015; Rhodes, 2015). Slingerland and others' (1996) model that proposes counter-clockwise circulation in the WIS during the Turonian may explain the PRB paleocurrent directions.

Wall Creek

Interpretations of the Wall Creek's depositional environment are diverse and continue to be debated. Numerous depositional models have been proposed for the Frontier Formation as a whole, but this discussion will focus solely on specific references to the upper Wall Creek Sandstone. The most commonly proposed Wall Creek depositional environment is a prograding, top-truncated deltaic system influenced by waves, tides, and/or storms (Barlow and Haun, 1966; Winn and others, 1983; Lee and others, 2005, 2007; Sadeque, 2006; Gani and Bhattacharya, 2007; Sadeque and others, 2009; Anna, 2010). Other authors, however, suggest the Wall Creek represents nearshore to offshore sand bars (Prescott, 1975; Merewether and others, 1979; Tillman and Almon, 1979), channelized distributary systems (Winn, 1986), storm current-dominated shelf sheets (Winn, 1991), or shelf sand ridges or bodies (Winn and others, 1983; Gustason, 2015). More recent work by Melick (2013) interprets the Wall Creek Sandstone as a remnant strand line deposit subsequently reworked by storms and associated south-flowing longshore currents. Numerical modeling by Ericksen and Slingerland (1990) and Slingerland and others (1996) confirms the presence of storm-driven, predominantly southern longshore currents near the microtidal western margin of the Turonian seaway. Rhodes (2015) agrees with this depositional setting, but specifies a transitional environment for the Wall Creek Sandstone from deltaic in the northern portion of the PRB to a microtidal and barrier/restrictive bay in the south. A consistent interpretation for almost every proposed depositional environment is that storms and currents were a major contributor to the redistribution of the original Wall Creek deposits.

Turner

While many authors group the Turner into the same depositional environment as the Wall Creek, including those previously described by Merewether and others (1979), Winn (1991), and Gustason (2015), others propose the Turner's environment was distinct from the Wall Creek. Interpretations by Merewether (1980, 1996) suggest the Turner was deposited in a more distal setting than the Wall Creek, with shelf sand bars fed by high-energy deltas. Weimer and Flexer (1985) describe a sequence of depositional settings for the Turner that began with lowstand incision into the underlying Pool Creek and Greenhorn formations through which shelf-edge conglomerates were deposited as the base of the Turner. As sea levels rose, an intertidal environment deposited sediment within the incised valleys, eventually transitioning to a deeper marine shelf on which the uppermost Turner sands were deposited. A similar sequence is described by Rice and Gaskill (1988) and Rice and Keighin (1989), who suggest that as sea levels rose during the late Turonian, a storm- and wave-influenced shelf and channel setting deposited the lower Turner, but upper Turner sediments were deposited below fair weather wave base. Charoen-Pakdi and Fox (1989) interpreted their lower Turner unit as a shallow shelf bar. Melick (2013) also describes the Turner as being deposited below fair weather wave base on a shallow shelf, but specifies that sediment input was from hyperpycnal (sediment gravity) flows. A recent study by Heger (2016) agrees with Melick's (2013) general shelf environment and sediment transport process, but proposes that the lower Turner was deposited near storm wave base.

Wall Creek and Turner Correlation

Their similar ages and proximal-to-distal depositional environments have led many authors to correlate the Wall Creek and Turner sandstones. Hancock (1920a, b) is the first to have suggested an association between the two sandstones. Other preliminary parallels were drawn between the Wall Creek and Turner by Downs (1949), Hose (1955), Faulkner (1956), Haun (1958), Goodell (1962), Barlow and Haun (1966), Merewether and others (1977), and Tillman and Almon (1979). One of the most useful correlations of the two sandstones is Merewether and others' (1979) correlation of their oldest and middle Wall Creek sandstone units (units VI and VII) to the Turner lithologies in the eastern PRB.

Cross sections, chronostratigraphic profiles, and isopach and structure contour maps that specifically relate the Wall Creek and Turner sandstones have been published by Merewether and others (1977), Merewether (1980, 1996), Merewether and others (2011), and Melick (2013). Most subsequent studies briefly refer to the Wall Creek and Turner as chronological equivalents but do not provide any other basis for their association.

Depth and Thickness

The first bedrock maps showing the Wall Creek and Turner as separate units were Barnett's (1915) geologic map of the southern PRB Big Muddy dome and Knetchtel and Patterson's (1958) 1:48,000-scale map of the northern Black Hills bentonite district. Subsequent maps of the Wall Creek and Turner sandstones in the PRB were produced by Mapel and Pillmore (1963, 1964), Robinson and others (1964), Curry (1979), Sutherland (2007, 2008), and Wyoming State Geological Survey (WSGS) bedrock maps in which the top of the mapped Frontier Formation is assumed to be the Wall Creek Sandstone (Ver Ploeg and Greer, 1987a, b; Ver Ploeg and Boyd, 2002; Ver Ploeg, 2004; Ver Ploeg and others, 2004; Hunter and others, 2005; Wittke, 2007; McLaughlin and Ver Ploeg, 2008; Lynds and others, 2014).

Individual sand thickness and unit depth (structure contour) maps of the Wall Creek were previously generated by Nowels (1924), Towse (1952), Goodell (1962), Prescott (1975), Merewether and others (1979), Merewether and Cobban (1986b), Gani and Bhattacharya (2007), and Rhodes (2015). Reeside (1944) created the first map detailing the thickness of the upper portion of the Carlile Shale, and Weimer and Flexer (1985) published an isopach map of the Turner, along with well log cross sections detailing its interpreted depth and thickness.

The WSGS, funded in part by the U.S. Geological Survey's National Coal Resources Data System project, interpreted Upper Cretaceous formation tops throughout the Powder River Basin. Wall Creek and Turner tops from 1,554 wells were combined with outcrop elevations from Wyoming's 30-meter digital elevation model, and input into ESRI's ArcGIS inverse distance weighted (IDW) tool to create structure contours (subsea elevation) of the reservoir top (fig. 4).

A thickness surface was also created using the same IDW tool and default parameters. The data inputs for this surface were the vertical difference in subsea elevations between the Wall Creek and the Belle Fourche Member of the Frontier Formation, and the difference in subsea elevations between the Turner and either the Pool Creek Member of the Carlile Shale or the Greenhorn Formation (fig. 5). Because no correction for the minimal regional dip was made, this thickness surface is termed an isochore. Appendix 3 contains the original depth-to-reservoir and isochore raster surfaces for the contour lines shown in figures 4 and 5.

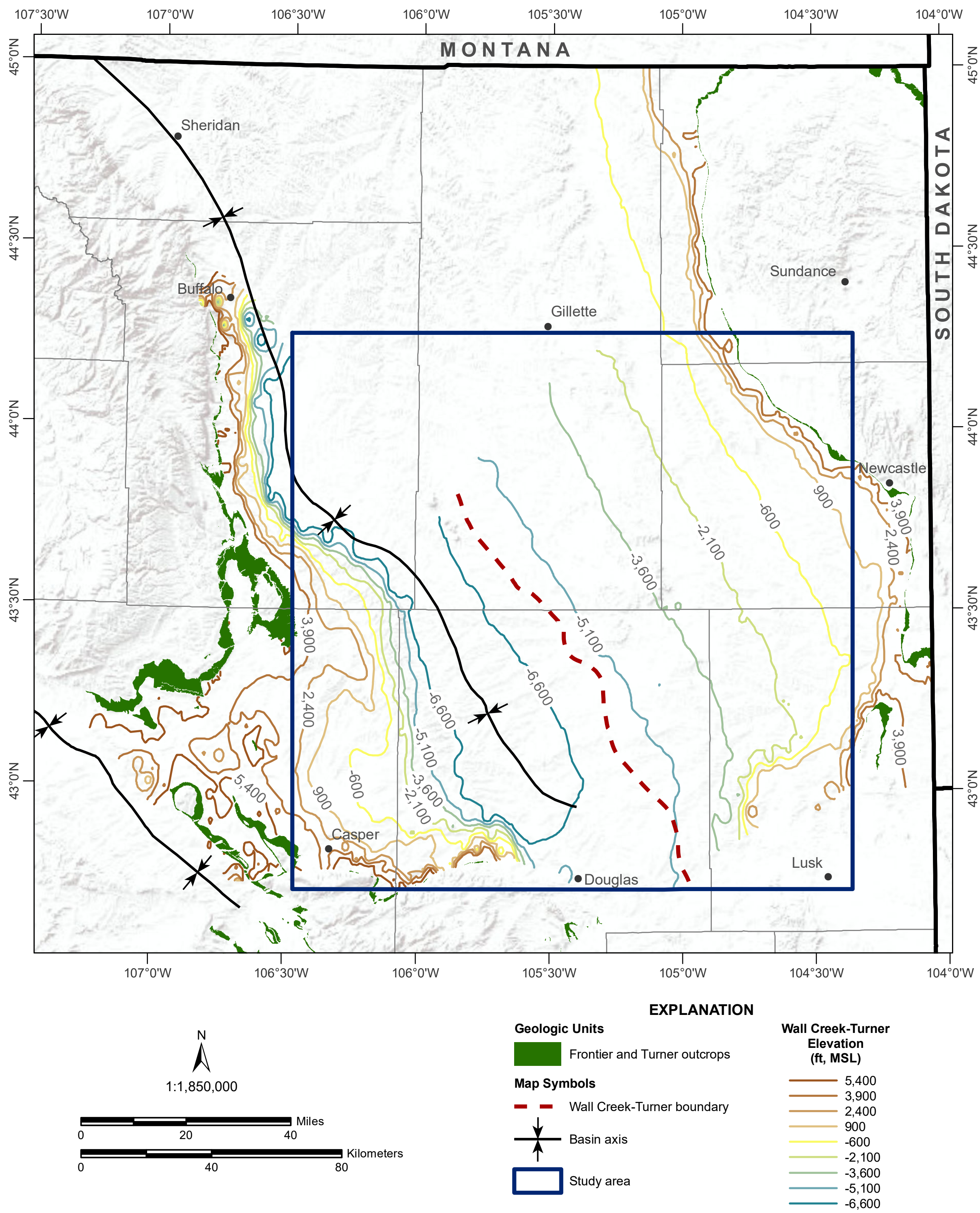

Figure 4. Structure map of the top of the Wall Creek and Turner sandstones. Elevation is relative to mean sea level (MSL). The Wall Creek is generally located in the western portion of the basin, while the Turner Sandstone is found in the east.

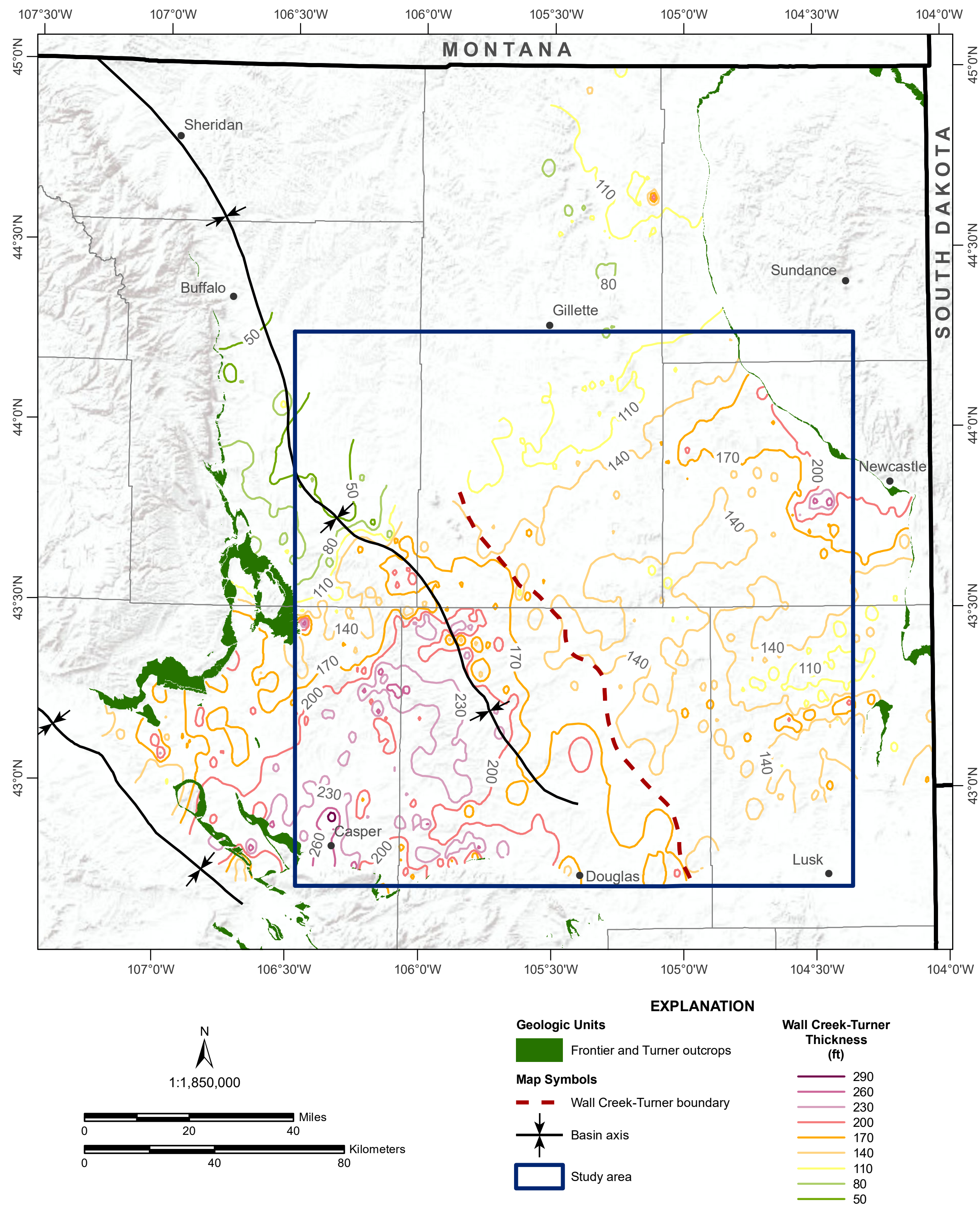

Figure 5. Isochore map of the Wall Creek and Turner sandstones. The Wall Creek Sandstone thickness is measured to the top of the Belle Fourche Member of the Frontier Formation. The Turner Sandstone thickness is measured to either the Pool Creek Member of the Carlile Shale or the Greenhorn Formation.

The spatial extent of Wall Creek and Turner nomenclature varies greatly between operators, drillers, authors, and public databases, which can affect accurate comparisons of the two sandstones. Using the WSGS' interpretations, this study standardizes the boundary between the Wall Creek and Turner with a schematic line separating them (red dashed line, figs. 4 and 5). The Wall Creek is located west of the line, and the Turner lies to the east. If necessary, the producing reservoirs of all wells in this study were adjusted to be consistent with the WSGS' reservoir boundary.

Wall Creek

The Wall Creek forms prominent ridges and dip slopes along the eastern flank of the Bighorn Mountains and the southern end of the Powder River Basin near Glenrock and Douglas, Wyoming. In outcrop, it is thickest in the southwestern portion of the PRB, where Rhodes (2015) describes an approximately 230-ft-thick measured section on the Emigrant Gap Anticline west of Casper, Wyoming. Wall Creek exposures thin northward to less than 125 ft (Merewether, 1980), eventually pinching out north of Buffalo, Wyoming. Isopachs by Melick (2013) and isochores shown in figure 5 indicate the Wall Creek reaches a maximum subsurface thickness of nearly 300 ft in a trend paralleling the basin's axis. It thins basinward to approximately 125 ft, although Rhodes (2015) suggests that there is localized thickening of the Wall Creek to the east before it thins.

Turner

The Turner crops out along the eastern margin of the PRB as low ridges with a maximum thickness of 260 ft near the Black Hills Uplift (Cobban, 1952; Weimer and Flexer, 1985). In the subsurface, however, the Turner reaches a maximum thickness of nearly 300 ft in western Weston County (fig. 5). It thins to 80–120 ft toward the west and averages 150–200 ft throughout the basin (Weimer and Flexer, 1985).

RESERVOIR CHARACTERIZATION

The Wall Creek and Turner sandstones have long been known as productive hydrocarbon reservoirs. Wegemann (1911) was one of the first to identify the Wall Creek as the primary producing reservoir at Salt Creek field, while the Turner was first noted as an oil producer in northern Weston and southern Crook counties by Robinson and others (1964). Later publications referencing the Wall Creek and Turner sandstones as oil producers include Hose (1955), Barlow and Haun (1966), Prescott (1975), and Tillman and Almon (1979). Merewether and Claypool (1980), Momper and Williams (1984), Charoen-Pakdi and Fox (1989), Dolton and Fox (1996), Anna (2010), Melick (2013), Heger (2016), Rahman and others (2016), Bottjer and others (2017), and Gustason (2017) published comprehensive datasets on Wall Creek and Turner hydrocarbon generation and migration, burial history, thermal maturity, porosity and permeability, source rock evaluation, and oil chemistry. Mitchell and Rodgers (1993) were one of the first to suggest the Turner as a potential unconventional reservoir target.

Hydrocarbons

Wall Creek

While the Mowry Shale has been proposed as the source rock for the Wall Creek reservoir (Momper and Williams, 1984; Dennen and others, 2005), other authors suggest hydrocarbon migration from the overlying Cody Shale or Niobrara Formation charged the Wall Creek (Merewether and Claypool, 1980; Anna, 2010; Rahman and others, 2016). Barlow and Haun (1966), Momper and Williams (1984), and Dennen and others (2005) suggest minor hydrocarbon migration from Frontier Formation shales.

Although primarily targeted for its prolific oil reserves, the Wall Creek also produces large amounts of natural gas. Values reported or calculated from initial production tests for upper Frontier sands indicate gas-to-oil ratios (GOR) average more than 4,650 cubic feet per barrel (ft^3/bbl; IHS, 2018; WOGCC, 2018). Crude oil American Petroleum Institute (API) gravities from the upper Frontier sands range from 29 degrees (°) to 68° and average 43.4° (WOGCC, 2018).

Turner

The Mowry Shale and Niobrara Formation are also considered the two possible source rocks for the Turner reservoir (Momper and Williams, 1984; Dolton and Fox, 1996; Anna, 2010; Rahman and others, 2016). Anna (2010) proposes that while the main source of Turner hydrocarbons is the overlying Niobrara Formation, migration along faults from the Mowry Shale is possible, especially in the eastern PRB where the Niobrara Formation did not reach the oil window. Rahman and others (2016) confirm contribution to the Turner from both the Mowry Shale and Niobrara Formation. However, migration from the Sage Breaks Shale Member of the Carlile Shale, the Belle Fourche Shale, and the Greenhorn Formation has also been suggested (Momper and Williams, 1984; Dolton and Fox, 1996).

The Turner reservoir also produces light crude oil and substantial primary natural gas. Initial production GOR from the Turner average 4,250 ft^3/bbl (IHS, 2018; WOGCC, 2018). Oil produced from the Turner has API gravities that vary from 32.6° to 62° and average 43° (WOGCC, 2018).

Porosity and Permeability

Wall Creek

Several of the Wall Creek's laminated and bioturbated facies exhibit high permeabilities ranging from 10 millidarcies (mD) to more than 100 mD, although typical Wall Creek permeability is less than 1 mD (Anna, 2010; Melick, 2013; Bottjer and others, 2017). Porosity in the Wall Creek can also be highly variable, ranging from <1–20 percent, with the highest porosities found in the hydrocarbon-bearing laminated and cross-bedded sandstones (Anna, 2010; Melick, 2013; Rhodes, 2015; Bottjer and others, 2017). These lithofacies with higher porosity and permeability led Bottjer and others (2017) to categorize the Wall Creek Sandstone as a "hybrid 'tight' oil" reservoir with a "conventional component."

Turner

Heger's (2016) core analyses suggest the fine-grained, highly bioturbated facies exhibiting 8–12 percent porosity are the best reservoirs within the Turner. This 8–12 percent porosity range is average for the Turner, with most authors reporting porosities within a range of 3–18 percent (Melick, 2013; Bottjer and others, 2017; Gustason, 2017). Porosity as high as 28 percent has been noted in samples from the Turner at Todd field in Weston County, but overall still averaged 9 percent (Charoen-Pakdi and Fox, 1989). Permeability within the entire Turner reservoir is typically reported as less than 5 mD and usually less than 1 mD (Charoen-Pakdi and Fox, 1989; Melick, 2013; Heger, 2016; Bottjer and others, 2017; Gustason, 2017). Charoen-Pakdi and Fox (1989), Rice and Keighin (1989), and Anna (2010) are exceptions to this, reporting permeability maximums of 17 mD, 100 mD, and more than 2 darcies, respectively, in medium-grained Turner samples. The low-permeability Turner is classified as a "true tight oil" reservoir by Bottjer and others (2017).

PRODUCTION TRENDS

Overview

Production data in the following sections are from the WOGCC's September 2018 well header and production download, with production reported through July 2018. As of this download, 27 operators in the Powder River Basin completed and produced from 474 horizontal wells in the Wall Creek (170 wells) and Turner (304 wells; fig. 6). An additional 1,903 vertical and directional wells have also produced from these reservoirs, 12 of which were later converted to horizontal wells. These 2,365 wells define an approximately 11,350-mi^2 study area in the south-central portion of the PRB. Recent drilling and production activity is focused in southern Campbell and northern Converse counties.

The production and completion data used in this investigation were queried from the WOGCC (2018), which has diverse data sources and reservoir nomenclature. Well data associated with a reservoir clearly not the upper sandstone of the Frontier Formation or Carlile Shale (e.g. Frontier-2, Frontier-3, Frontier-4, Billy Creek Sand, 2nd Wall Creek) were eliminated from this study's dataset. Because the WOGCC database is primarily production oriented, however, it is likely that the thickest and most hydrocarbon-rich sands in the Frontier Formation and Carlile Shale—the Wall Creek and Turner—were the operators' target. As such, any well referencing the Frontier, Wall Creek, or Turner reservoirs was included and will be referred to as the "Wall Creek" and "Turner" in the following comparisons and analyses. All wells were reviewed and their producing reservoirs standardized to correspond to the WSGS-defined Wall Creek-Turner spatial reservoir extents.

Although oil is the main focus of operators producing from the PRB Wall Creek and Turner reservoirs, large amounts of natural gas are also extracted from these reservoirs, either as a by-product or as a primary production target. Natural gas production is therefore included in this study's comparisons and analyses.

First Months Production

The first 3, 6, 9, 12, and 18 months of oil and natural gas production were calculated for each horizontal well by summing their respective months' non-zero production. Any month in which a well produced either oil or gas was included in both products' sums. Because well site or transport issues can affect initial production and sales, wells producing less than 15 days during their first month online had that production incorporated into the next three months' production. Cumulative values for all horizontal wells were also summed and used in production cross-plots. Initial production for all horizontal wells was also recorded from WOGCC well completion reports and production tests. Full names of operators are listed in table 1. All well production data compiled for this study, along with respective WSGS producing reservoir designations, are available in Appendix 1.

Each Wall Creek- and Turner-producing horizontal well's first 6, 12, and 18 months of production was plotted against their respective cumulative production (figs. 7 and 8) and their respective average rate of daily production (figs.

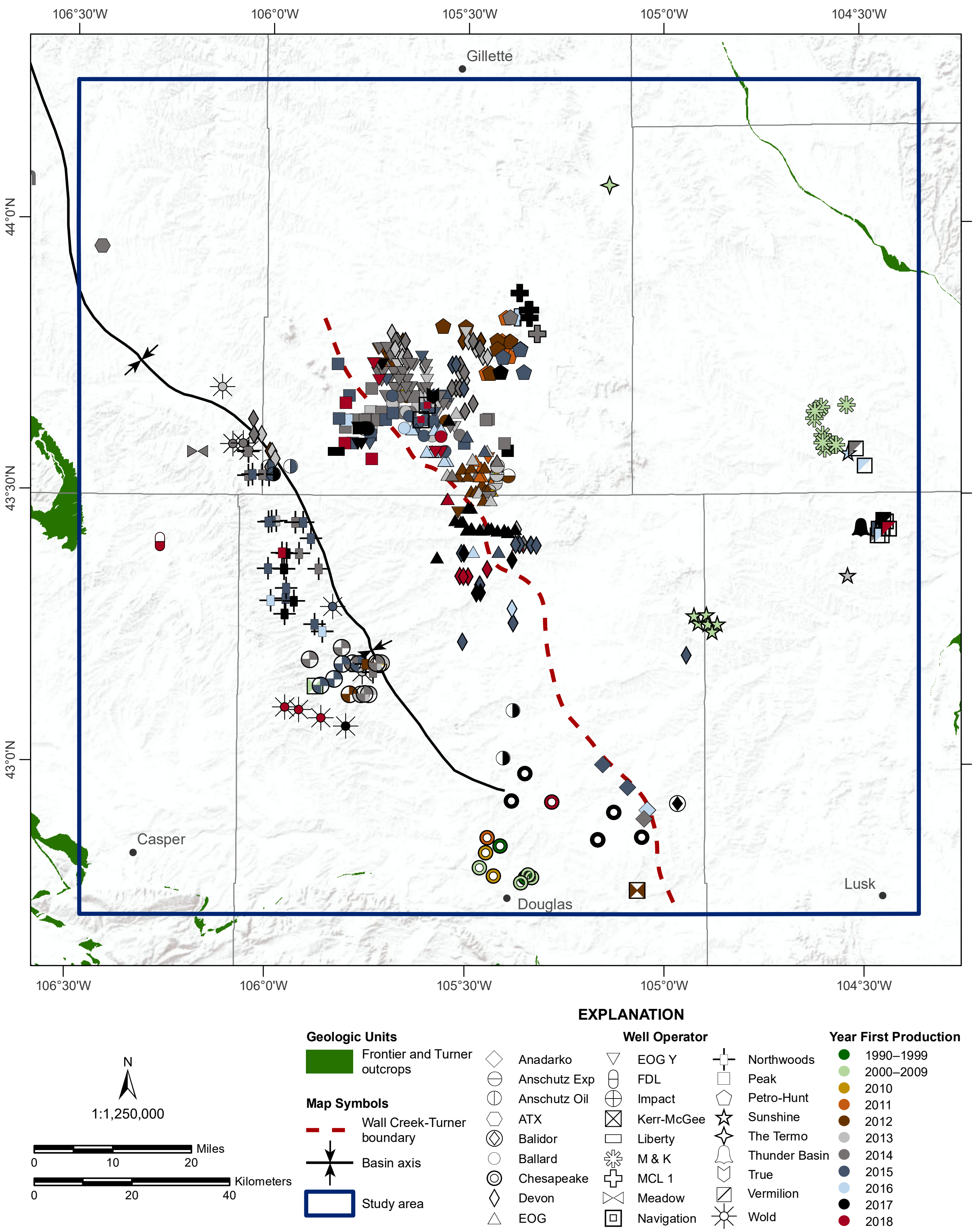

Figure 6. Horizontal wells producing from the Wall Creek and Turner reservoirs. Wells are colored by year of first production; well operator is represented by symbol shape.

Table 1. Operator abbreviations and full names.

Operator abbreviation	WOGCC operator full name
Anadarko	Anadarko E&P Onshore LLC
Anschutz Exp	Anschutz Exploration Corporation
Anschutz Oil	Anschutz Oil Company LLC
ATX	ATX Energy Partners LLC
Balidor	Balidor Oil & Gas LLC
Ballard	Ballard Petroleum Holdings LLC
Chesapeake	Chesapeake Operating LLC
Devon	Devon Energy Production Company LP
EOG	EOG Resources Inc
EOG Y	EOG Y Resources INC
FDL	FDL Operating LLC
Impact	Impact Exploration & Production LLC
Kerr-McGee	Kerr-McGee Oil & Gas Onshore LP
Liberty	Liberty Resources Management Co LLC
M & L	M & K Oil Company LLC
MCL 1	MCL 1 Oil & Gas Wyoming LLC
Meadow	Meadow Deep LLC
Navigation	Navigation Powder River LLC
Northwoods	Northwoods Operating LLC
Peak	Peak Powder River Resources LLC
Petro-Hunt	Petro-Hunt LLC
Sunshine	Sunshine Valley Petroleum
The Termo	The Termo Company
Thunder Basin	Thunder Basin Resources LLC
True	True Oil LLC
Vermilion	Vermillion Energy USA LLC
Wold	Wold Energy Partners LLC

9 and 10) for each operator. Average daily production rate is a well's cumulative production divided by the total number of days it has produced. Initial production and the first 3 and 9 months of production are not displayed as cross-plots, as the first 6, 12, and 18 months sufficiently demonstrate production trends. In order to identify production trend differences between the reservoirs and eliminate visual crowding on the graphs, the Wall Creek and Turner are shown on separate plots.

Although a few operators in figures 7–10 consistently have higher mean production, even those with the highest-producing wells also have poorer performing wells. The exception is Impact Exploration and Production, whose wells consistently achieve higher oil production. It should also be noted that the majority of EOG Resources wells with high gas production in figures 8 and 10 are permitted as gas wells, while all but one of the equally high gas-producing Peak Powder River Resources wells are permitted as oil wells.

The production data in these plots converge to more linear trends over time, but with shallower slopes. This suggests that Wall Creek and Turner wells with initial high production continue to be successful throughout their first year and a half, although the rate of production slows. The trendline regression coefficients (R^2) increase throughout the wells' first 18 months of production. Pearson correlation coefficients (R) also appear to indicate better correlation between the production variables as wells age, although the increasing R values may be biased by younger wells' first 18 months of production being nearly equivalent to their cumulative production. However, all timeframes do indicate a strong positive correlation between first months and cumulative well production.

The one exception to increasing R and R^2 values is the Wall Creek wells' average daily gas production, which shows a slight decline in the 12 and 18 months' coefficients compared to the first 6 months of production (fig. 10). A possible explanation is that only 9 of the 170 Wall Creek wells are permitted as gas wells. Although Wall Creek wells initially have high average daily rates of gas production, this rate decreases as gas production becomes mostly gas associated with oil production.

The trends demonstrated in the first 18 months of production charts (figs. 7 and 8) suggest that this timeframe is a good proxy for ultimate well production outcomes. Evaluating the first 18 months of production also normalizes the dataset by disregarding when a well first came online. Because this standard timeframe is available for 81 percent of the wells in the study area, all subsequent graphical plots will only evaluate Wall Creek-Turner wells with 18 months of production.

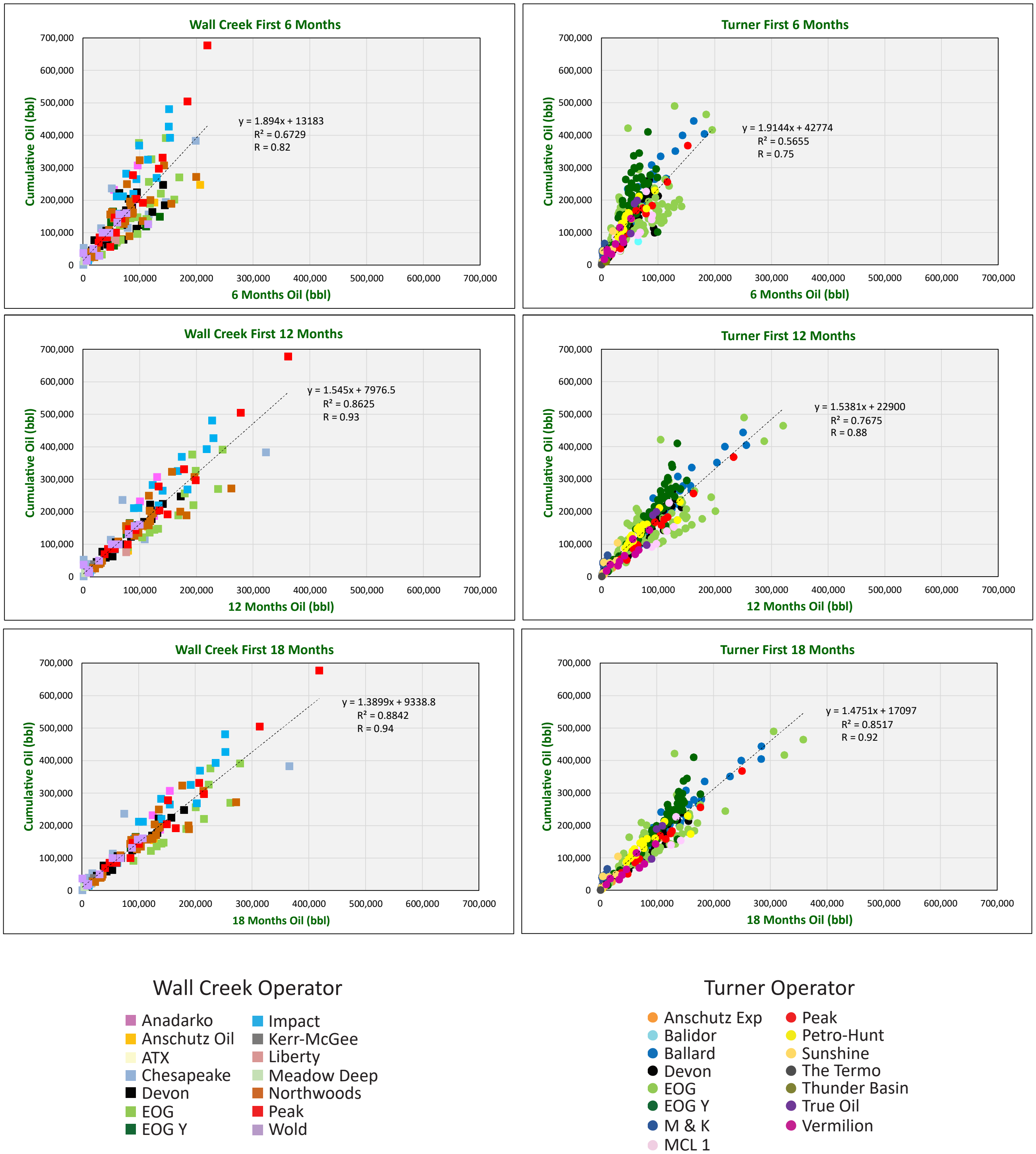

Figure 7. Cumulative versus first 6 months (top row), 12 months (middle row), and 18 months (bottom row) of unconventional oil production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with the respective months' production.

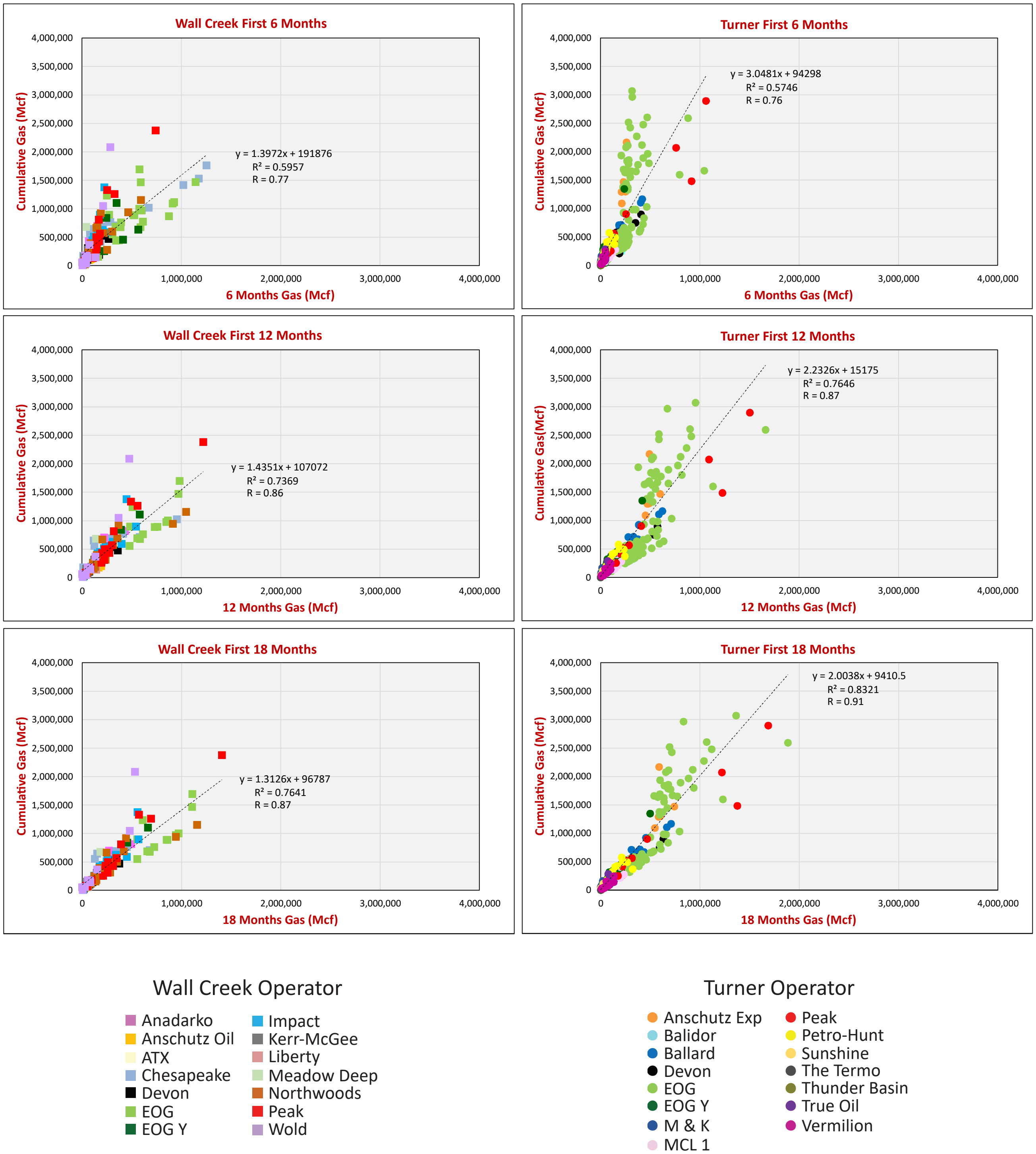

Figure 8. Cumulative versus first 6 months (top row), 12 months (middle row), and 18 months (bottom row) of unconventional gas production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with the respective months' production.

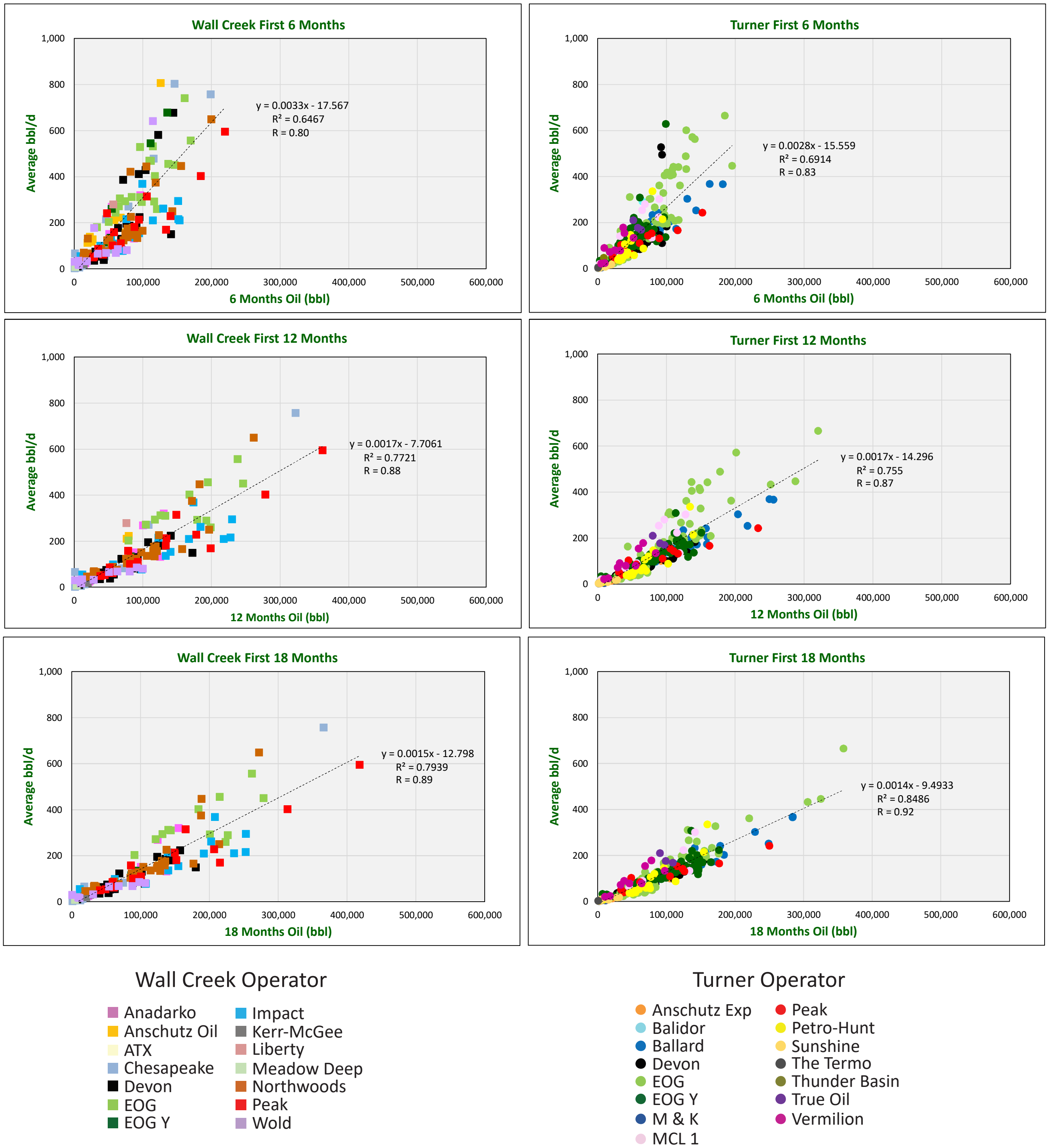

Figure 9. Average daily versus first 6 months (top row), 12 months (middle row), and 18 months (bottom row) of unconventional oil production. Average daily oil production is reported in barrels/day (bbl/d) and is calculated as a well's cumulative oil production compared to its total number of production days. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with the respective months' production.

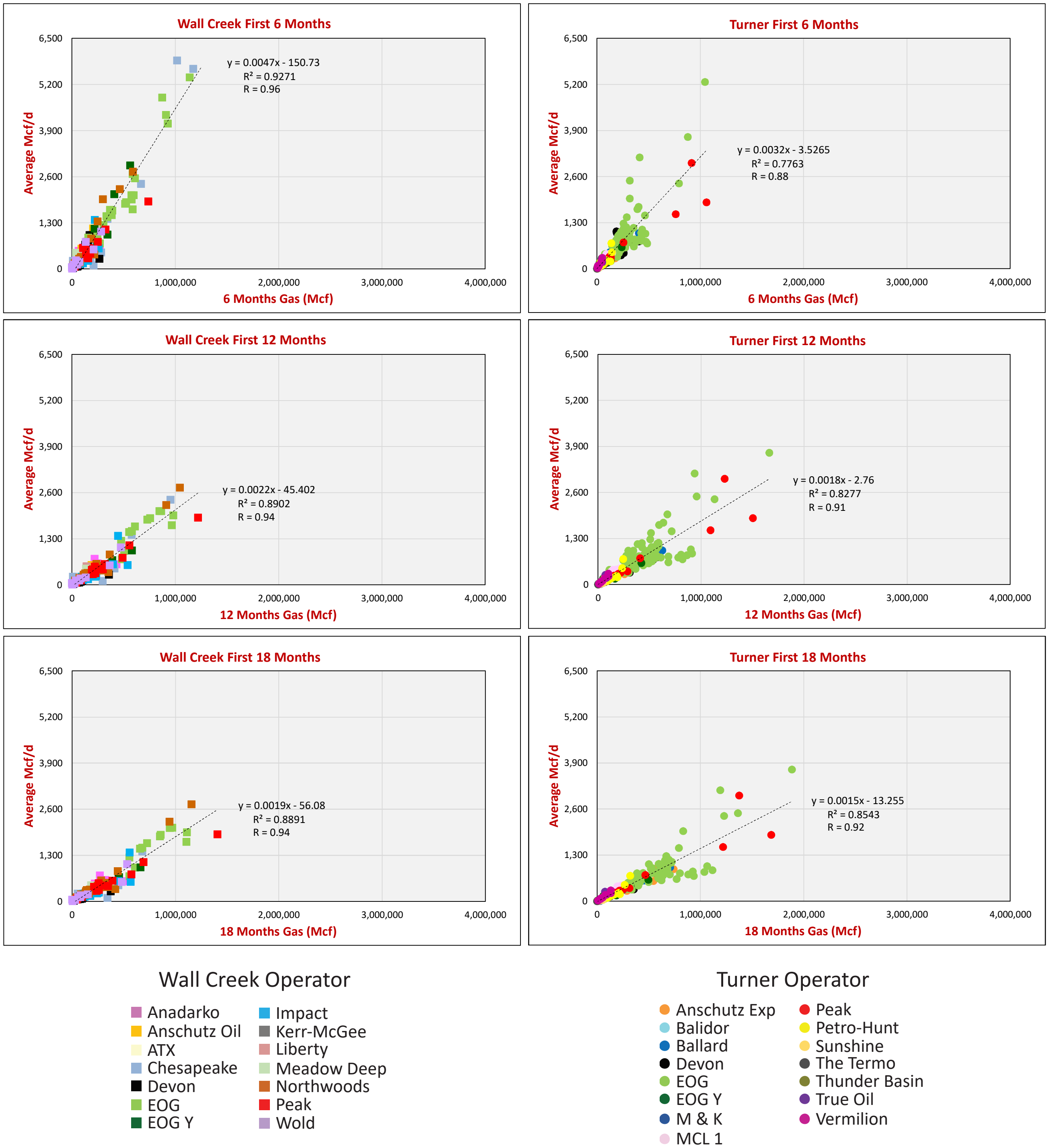

Figure 10. Average daily versus first 6 months (top row), 12 months (middle row), and 18 months (bottom row) of unconventional gas production. Average daily gas production is reported in million cubic feet/day (Mcf/d) and is calculated as a well's cumulative gas production compared to its total number of production days. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with the respective months' production.

Production Over Time

Figures in Appendix 2 show each operator's monthly oil and gas production from January 2008 to July 2018. A line represents an individual well and is colored based on the year the well first produced. Because production from the Wall Creek and Turner is not differentiated in these figures, each operator is represented by a single chart, even if they own wells producing from both reservoirs (e.g. Devon). Figure 6 displays the wells' spatial locations.

The Appendix 2 figures highlight several operator-specific production trends. Wells with both the highest monthly production peaks and the best first 18 months of production are operated by the same company (figs. 7 and 8). Most operators have managed to maintain consistent oil production peaks through time (e.g. Impact, Peak, and Petro-Hunt) or even increase their peak oil production (e.g. Ballard, EOG, EOG Y, and Northwoods). However, newer Anschutz Oil and Chesapeake wells exhibit substantial peak oil production increases compared to these operators' older wells. Continued production monitoring will determine whether these spikes are outliers or are consistent improvement trends for Anschutz Oil and Chesapeake.

Operators' gas production through time generally mimics that of their oil production, but with even more consistent decline trends. Chesapeake, EOG, Northwoods, and Peak show increasingly higher gas production peaks in their newer wells. Except for one Peak gas well completed in 2017, these higher gas peaks are from oil wells.

A few operators have also been able to extend their peak production past the steep decline curve typical of horizontal wells. Broader oil production peaks are especially noticeable in Impact and Peak wells and in Chesapeake wells first producing in 2017. These 2017 Chesapeake wells and most EOG wells also have extended high gas production. More production data over longer timeframes are needed to confirm or disprove these trends. The differences between operators' peak monthly production and decline curves suggest possible differences in their drilling and completion practices.

WELL CHARACTERISTICS VERSUS PRODUCTION

Well Laterals

Producing Interval Length

Because production success in the similarly aged Codell Sandstone in the Wyoming portion of the Denver Basin correlates to longer well laterals (Toner and Campbell, 2017), horizontal well lateral length was examined for the Wall Creek and Turner reservoirs in the Powder River Basin. This study uses a more refined representation of length than approximated by Toner and Campbell (2017). Lengths for PRB Wall Creek-Turner production are termed "producing interval lengths" and are equivalent to the perforated and hydraulic frac stage interval reported on each horizontal well's completion report. Although not evaluated in the following figures, Appendix 1 also documents whether each well has a cemented liner, which can affect frac placement and production.

Figure 11 is a cross-plot of Powder River Basin horizontal wells' producing interval lengths and their first 18 months of Wall Creek-Turner production. The shortest producing interval length is reported as only 20 ft long (API number 49-009-28137). This is likely a reporting error, since the rest of the shortest producing intervals cluster around 1,000 ft. The longest producing interval is more than 10,350 ft (API number 49-009-30929). Sixty-five percent of horizontal wells in the study area have 3,000- to 5,000-ft producing interval lengths, and average more than 92,000 bbl oil and 253,000 Mcf gas during their first 18 months of production (table 2). Only 20 percent of horizontal Wall

Table 2. Average 18 months production for wells with 3,000–5,000 ft and 8,000–10,000 ft producing intervals.

Reservoir	Product	3,000–5,000 ft producing interval average 18 months production *(standard deviation)*	8,000–10,000 ft producing interval average 18 months production *(standard deviation)*
Wall Creek	oil (bbl)	105,736 *(80,378)*	130,560 *(71,317)*
Wall Creek	gas (Mcf)	254,936 *(287,063)*	359,990 *(289,435)*
Turner	oil (bbl)	88,591 *(51,176)*	115,275 *(77,568)*
Turner	gas (Mcf)	253,586 *(291,305)*	525,980 *(587,470)*
Wall Creek-Turner combined	oil (bbl)	92,119 *(58,628)*	126,806 *(72,494)*
Wall Creek-Turner combined	gas (Mcf)	253,863 *(289,920)*	400,760 *(384,893)*

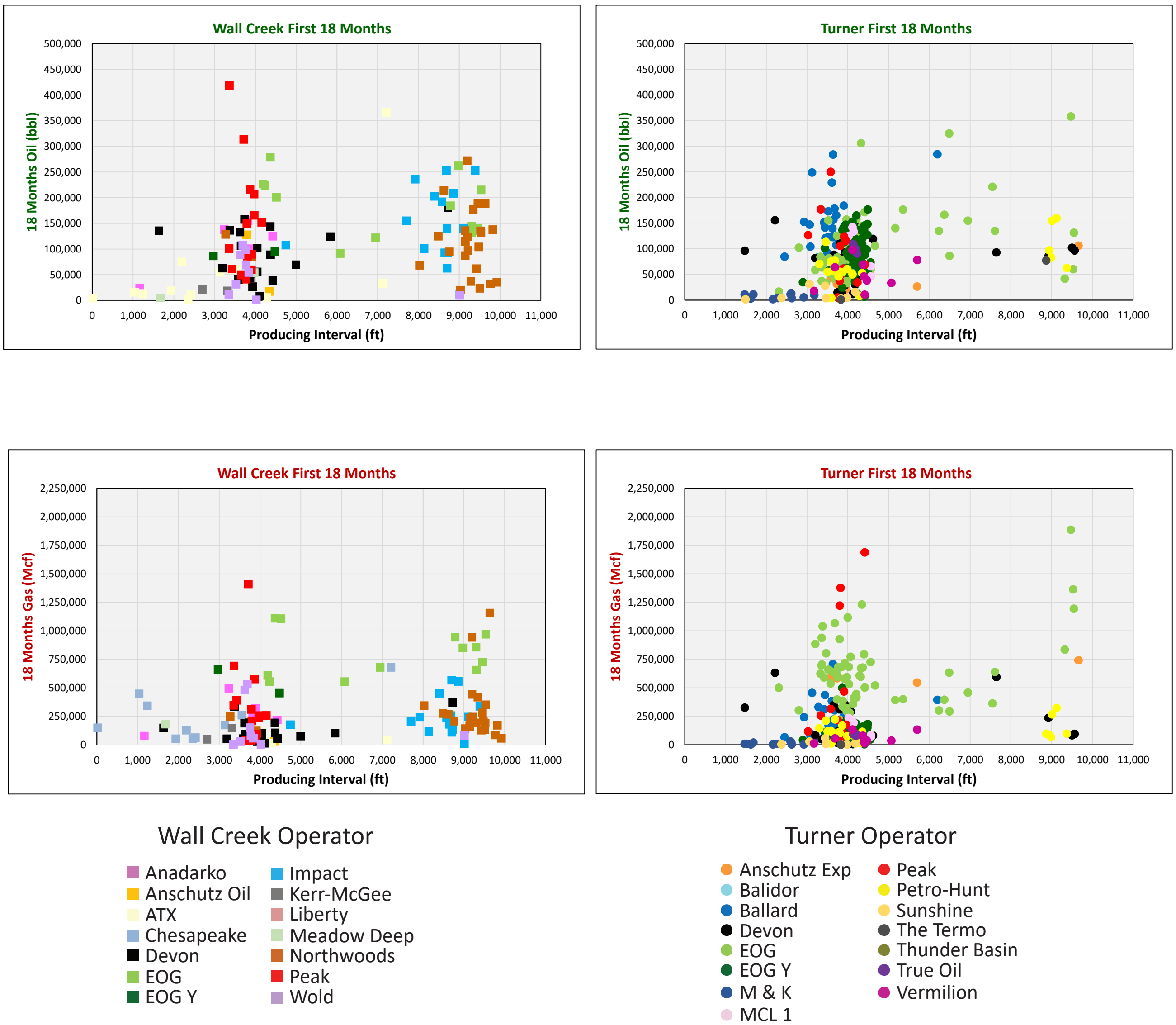

Figure 11. Producing interval length versus first 18 months of unconventional oil (top row) and gas (bottom row) production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

Creek-Turner wells produce from intervals longer than 8,000 ft, although they have average 18 months of oil and gas production of more than 126,000 bbl and 400,000 Mcf, respectively (table 2). The longest producing interval lengths (more than 8,000 ft) are especially utilized within the Wall Creek reservoir.

Visually there is not a consistent correlation between longer producing intervals and improved oil and gas production. Horizontal Wall Creek and Turner wells 3,000–5,000 ft in length appear to perform as well as, if not better than, wells with longer producing intervals. This trend also applies to operators utilizing varying production lengths. Even operators that maintain a narrow range of producing interval lengths throughout all their wells have inconsistent production success.

When 18 months production averages are compared between wells with 3,000–5,000 ft and 8,000–10,000 ft producing interval lengths, longer interval wells do have higher average production, and especially higher average gas production (table 2). However, the highest-producing 8,000–10,000 ft wells may artificially elevate the production averages due to the much smaller population of this group. The large standard deviations of these averages also suggest uncertainty in whether drilling a longer lateral will have a consistent, corresponding increase in production.

Lateral Orientation

The orientation of a horizontal well's lateral in relation to regional and local stress fields can affect its production success. In order to intersect as many natural fractures as possible and to enhance induced fracture propagation, laterals are typically drilled perpendicular to the maximum horizontal stress direction (S_{Hmax}; Beard, 2011; Norbeck, 2011). The modern day S_{Hmax} in northeastern Wyoming has been interpreted as generally northeast–southwest (NE–SW; Zoback and Zoback, 1980; Billingsley, 2011), with Parks and Gale (1996) and Bottjer and others (2017) specifying S_{Hmax} azimuths of 70°–75° in the southern PRB.

To compare S_{Hmax} to operator drilling practices, the lateral orientations of all PRB Wall Creek and Turner horizontal wells were calculated from their surface-hole and bottom-hole locations and normalized to between 50°–230° by adding or subtracting 180° from the original azimuth. This allows well orientations that have opposite but complementary azimuths to be grouped together. Figure 12 compares horizontal wells' first 18 months of production to their normalized lateral orientations. To reduce bias from wells' lateral lengths, production values were also normalized by producing interval lengths and again plotted against lateral direction (fig. 13).

Figures 12 and 13 indicate that operators have drilled predominantly north–south-trending (N–S) Wall Creek and Turner laterals in the Powder River Basin. The average normalized lateral azimuth is 175° and 91 percent of all laterals are oriented within 30° of true N–S. Only 26 wells (6 percent) have normalized azimuths between 160° and 165°, directly perpendicular to S_{Hmax}.

Figures 12 and 13 also demonstrate that production from horizontal Wall Creek and Turner wells does not strongly depend on lateral orientation. Although the highest-producing wells are drilled N–S, those operators that restrict their laterals to a small N–S azimuth range still have noticeable spread in their wells' first 18 months of production. In addition, wells oriented in an east–west (E–W) direction are not necessarily outperformed by their N–S counterparts, especially in regard to Turner oil production.

Ballard, in particular, has achieved consistent oil production and oil production per foot in both its N–S and E–W Turner wells. Comparing three Ballard wells that first produced in 2013, are in close proximity to each other, and have similar producing interval lengths establishes that the E–W well (API number 49-005-61697) has better first 18 months oil production than the N–S wells (API numbers 49-005-61484 and 49-005-61486). When another E–W Ballard well that first came online in 2015 (API number 49-005-62463) is compared to five N–S Ballard wells (API numbers 49-005-62449, 49-005-62525, 49-005-62791, 49-005-63118, 49-005-62329) of similar location, age, and producing length, the E–W well again outperforms all but one of the N–S wells (API number 49-005-562791) in oil production at the 18-month mark.

A comparison of the two orientations' average production shows that N–S wells do have higher average production than E–W wells, especially those producing from the Wall Creek reservoir (table 3). The large standard deviations and small E–W population, however, again suggest uncertainty as to which lateral orientation will consistently yield higher production.

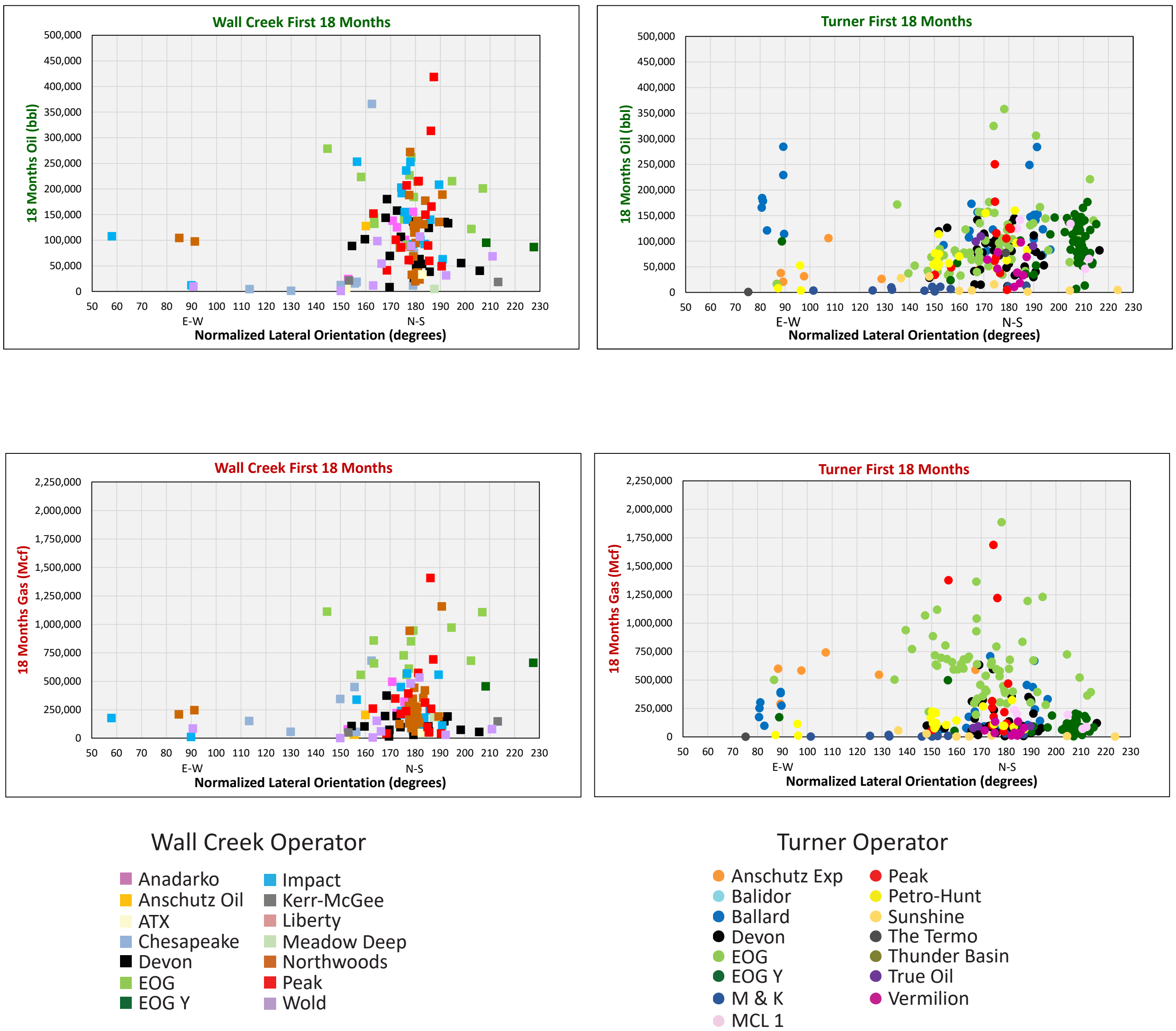

Figure 12. Lateral orientation versus first 18 months of unconventional oil (top row) and gas (bottom row) production. All lateral azimuths were normalized to 50°–230° to show east–west and north–south trends, respectively. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

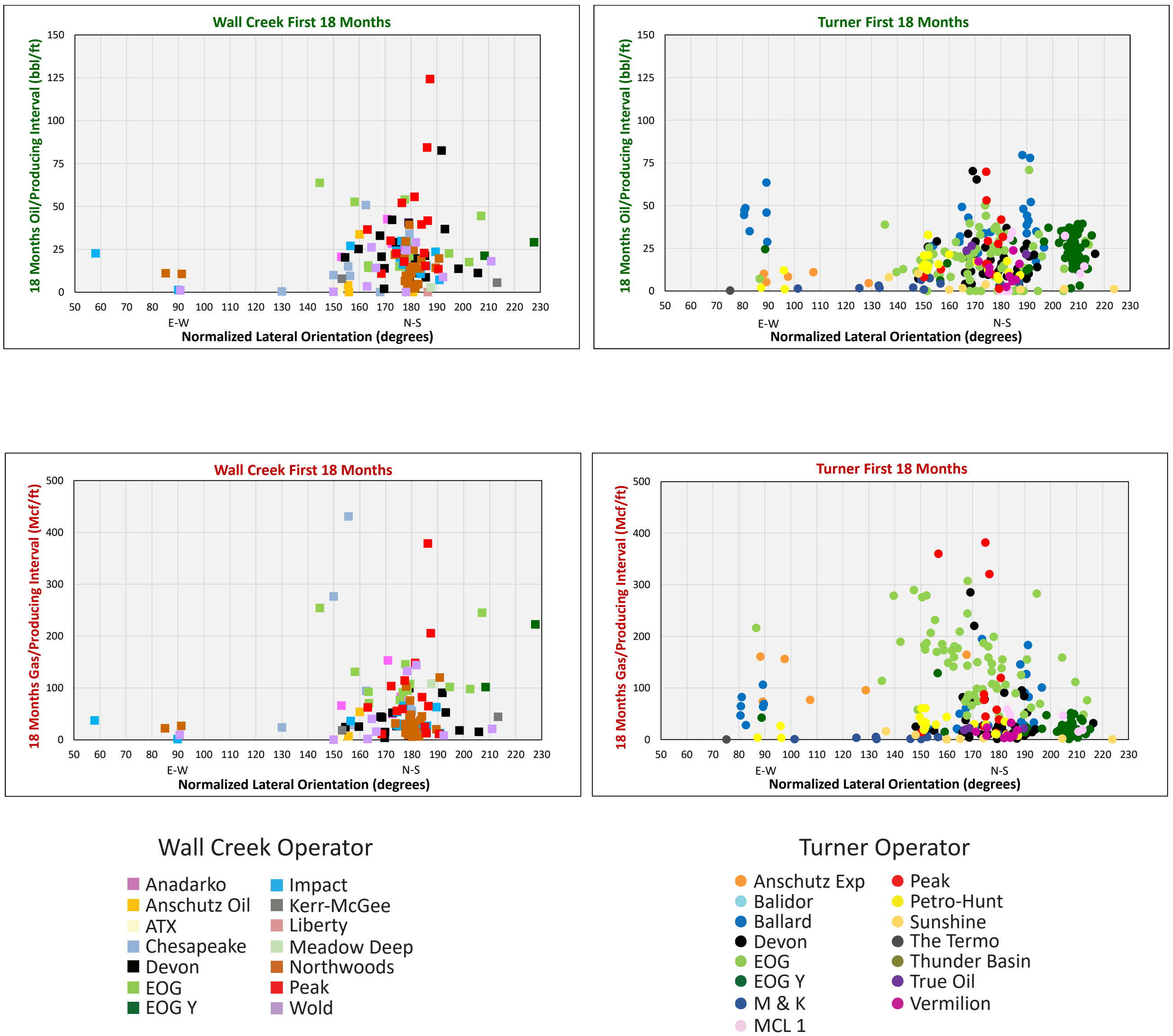

Figure 13. Lateral orientation versus first 18 months of unconventional oil (top row) and gas (bottom row) production normalized by producing interval length. All lateral azimuths were normalized to 50°–230° to show east–west and north–south trends, respectively. API number 49-009-28137 was not included on these figures because its reported 20-ft-producing interval is likely an error. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

Table 3. Average 18 months of production and standard deviation for wells with north–south and east–west lateral orientations.

Reservoir	Product	E–W lateral orientation average 18 months production *(standard deviation)*	N–S lateral orientation average 18 months production *(standard deviation)*
Wall Creek	oil (bbl)	55,599 *(52,076)*	119,819 *(76,037)*
Wall Creek	gas (Mcf)	136,663 *(108,997)*	293,582 *(270,807)*
Turner	oil (bbl)	91,204 *(82,273)*	95,489 *(63,009)*
Turner	gas (Mcf)	244,577 *(197,985)*	302,371 *(342,882)*
Wall Creek-Turner combined	oil (bbl)	84,422 *(83,881)*	105,039 *(69,276)*
Wall Creek-Turner combined	gas (Mcf)	224,022 *(187,152)*	298,905 *(315,777)*

Well Completion Practices

Because well lateral attributes do not appear to strongly influence how successful a Wall Creek-Turner well is in the Powder River Basin, well completion techniques were also evaluated. Horizontal wells' first 18 months of production were compared to the number of frac stages, the amount of slurry, and the amount of proppant used to complete each well (figs. 14–16). These data were recorded from available well completion reports submitted to the WOGCC. All wells in the study area are not represented on these charts due to incomplete information on their completion reports. In the case of slurry, volumes reported in units (e.g. gallons) not chosen as the standard unit (barrels, [bbl]) were excluded.

Figure 14 indicates that the majority of Wall Creek and Turner horizontal well completions use less than 40 frac stages. The largest number of frac stages are used in Turner wells. Operators generally use a narrow range of frac stages, but with variable production yields. Also, there does not appear to be a consistent association between an increasing number of frac stages and improved well production, even within the same operator's well group.

A comparison of well production to completion slurry volume suggests the same lack of correlation (fig. 15). With the exception of EOG, Northwoods, and Petro-Hunt, operators have not varied the amount of slurry used in their well completions. Even EOG, Northwoods, and Petro-Hunt wells do not consistently yield increased production with increased barrels of slurry.

Likewise, EOG, Devon, Northwoods, and Petro-Hunt are the only operators that use a wide range of proppant amounts (measured in pounds [lb]) to complete their wells (fig. 16). This may benefit some of these operators, as their wells display shallow positive linear oil production trends as proppant volumes increase. However, other wells owned by these same operators still match or outperform their oil and gas production with less proppant.

With a few exceptions, operators producing from the PRB Wall Creek and Turner do not vary how they complete their wells. Using the entire well dataset—including those without 18 months of production—Wall Creek and Turner wells are completed with an average of 21 frac stages, nearly 84,400 bbl of slurry, and 4,967,500 lb of proppant. Increasing the completion sizes does not appear to have a consistent corresponding increase in 18 months of production.

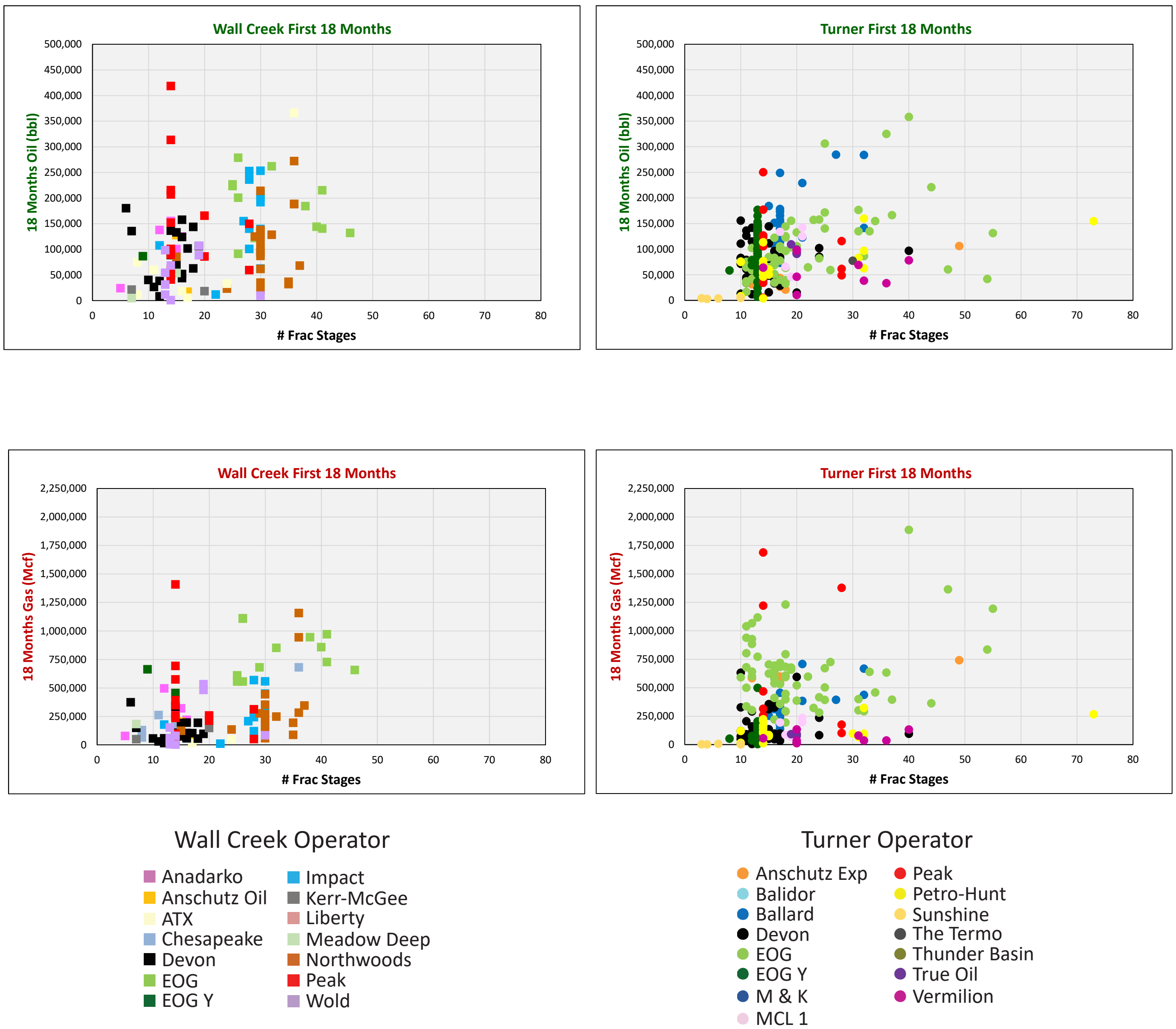

Figure 14. Number of hydraulic fracturing (frac) stages used in horizontal well completion versus first 18 months of unconventional oil (top row) and gas (bottom row) production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

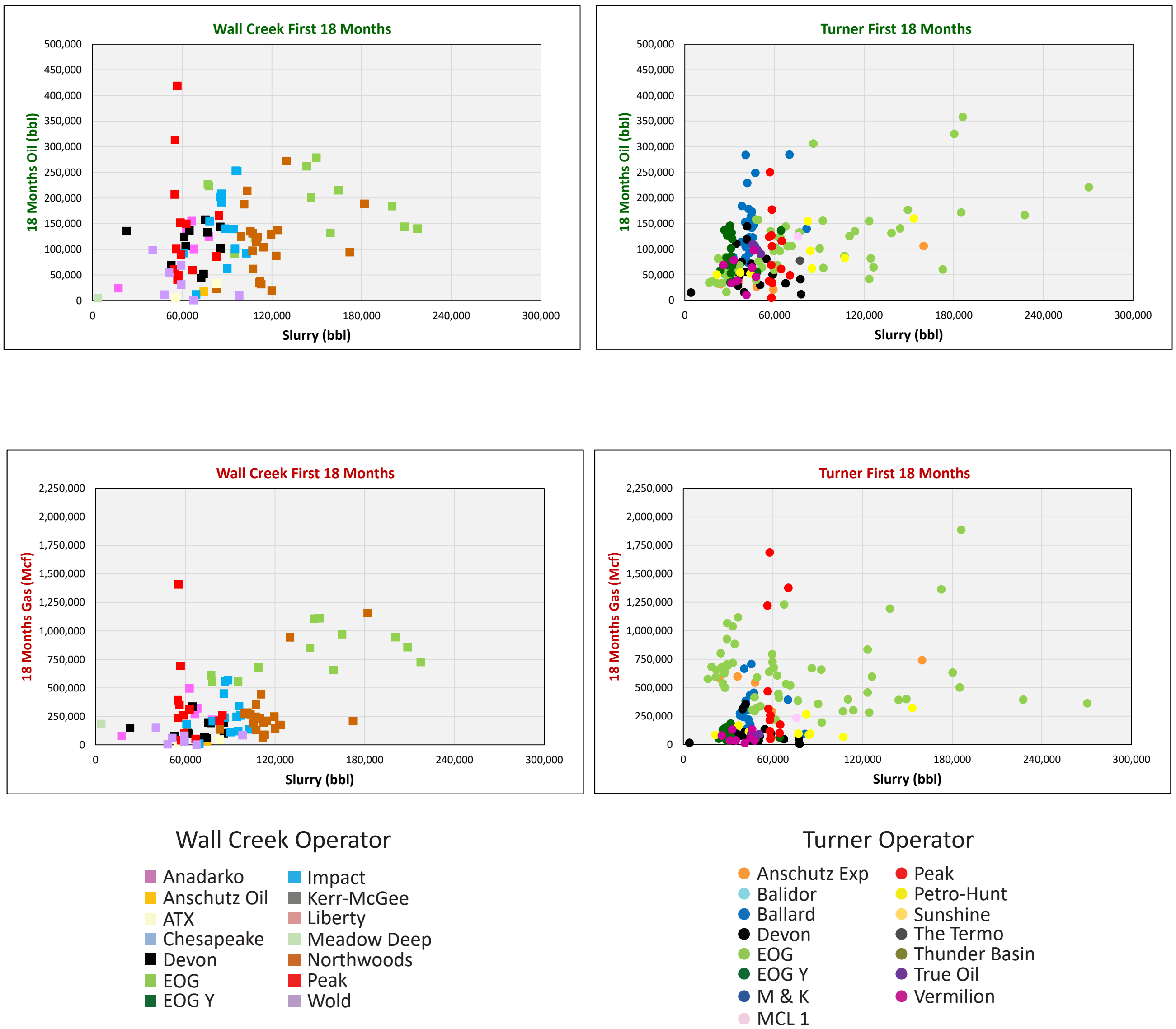

Figure 15. Volume of slurry used in horizontal well completion versus first 18 months of unconventional oil (top row) and gas (bottom row) production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

Figure 16. Amount of proppant used in horizontal well completion versus first 18 months of unconventional oil (top row) and gas (bottom row) production. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

RESERVOIR GEOLOGY VERSUS VERSUS PRODUCTION

The weak-to-absent correlation between how Wall Creek-Turner wells are drilled and completed and their production suggests that geology may influence oil and gas extraction from these reservoirs. The following section examines several geologic characteristics of the Wall Creek and Turner and their hydrocarbon products in an effort to explain horizontal production trends throughout the basin.

Because of the PRB's structural history, differences in reservoir depositional environments, and large areal extent, geologic variation is expected throughout the study area. The reservoirs' geologic characteristics are examined spatially by first using ArcGIS' inverse distance weighted (IDW) tool to create interpolated raster surfaces and associated contour lines from individual wells. The contour lines are then draped over production surfaces to visually evaluate each geologic attribute. Wells were not included on figures to reduce visual clutter.

Production raster surfaces were also interpolated from horizontal wells' first 18 months of oil and gas production. Because conventional completion practices were traditionally used to produce from the Frontier Formation and Carlile Shale, cumulative oil and gas production was also summed and spatially interpolated for all applicable vertical and directional Wall Creek- and Turner-producing wells in the PRB. The marked differences in completion techniques necessitates maintaining the conventional production (from vertical and directional wells) and unconventional production (from horizontal wells) in distinct datasets and limiting comparison of the two practices to general spatial trends.

Appendix 3 contains all reservoir production and geologic attribute raster surfaces. Each surface was clipped to the extent of the wells defining the WSGS' Wall Creek and Turner elevation (structure contour) and isochore.

Statistical correlations between each geologic attribute surface and the Wall Creek-Turner production surfaces were also calculated using an ArcGIS Band Collection Statistics tool. Each section below includes a table of R values (Pearson correlation coefficients) ranging from -1 to 1. These values represent the strength of correlation between the variables (0 indicates no correlation; ±1 indicates perfect correlation). The R value will be a positive number if, as one of the variables increases, the other variable also increases. Negative R values indicate that as one of the variables increases, the other decreases.

Depth and Thickness

Both conventional and unconventional oil production from the Wall Creek and Turner has been—and continues to be—focused on the deeper portions of the Powder River Basin parallel to the basin axis (figs. 17 and 18). Figure 19 confirms that the highest oil-producing horizontal wells are drilled to total vertical depths greater than approximately 10,000 ft. These deep, high-production areas do not always correspond to the thickest reservoir intervals, which occur near the far southwest and northeast basin margins (figs. 20 and 21). In fact, operators have been very effective in producing large amounts of oil from the thinner portions of these reservoirs. Correlation statistics in table 4 confirm that Wall Creek and Turner oil production has a strong positive correlation with depth, but a weak positive correlation with reservoir thickness.

PRB Wall Creek-Turner natural gas production differs somewhat from oil production. While conventional gas production spatially mirrors and is likely a by-product of oil production, horizontal wells do not display the same elevated natural gas production trend near the basin axis (figs. 22 and 23). Wall Creek-Turner horizontal wells produce the most natural gas from a narrow area extending northeast and up-dip from the deepest section of the basin. Compared to conventional gas production, this unconventional high-gas-producing area is spatially restricted to thinner portions of the reservoir and is not associated with unconventional oil production (figs. 24 and 25). Of the 54 unconventional gas wells producing from the PRB Wall Creek or Turner, 48 cluster in this high-gas area, and 4 more are permitted to be drilled (WOGCC, 2018). As with oil, depth has a stronger positive correlation with gas production than thickness (table 4), suggesting that gas-rich intervals are more likely to be found in deep, but not necessarily thick, reservoir intervals.

Table 4. Statistical correlation between Wall Creek-Turner unconventional and conventional oil and gas production surfaces and reservoir depth and thickness surfaces.

Wall Creek-Turner product	R value (depth)	R value (thickness)
unconventional first 18 months oil	0.90	0.26
unconventional first 18 months gas	0.69	0.24
conventional cumulative oil	0.65	0.08
conventional cumulative gas	0.41	0.11

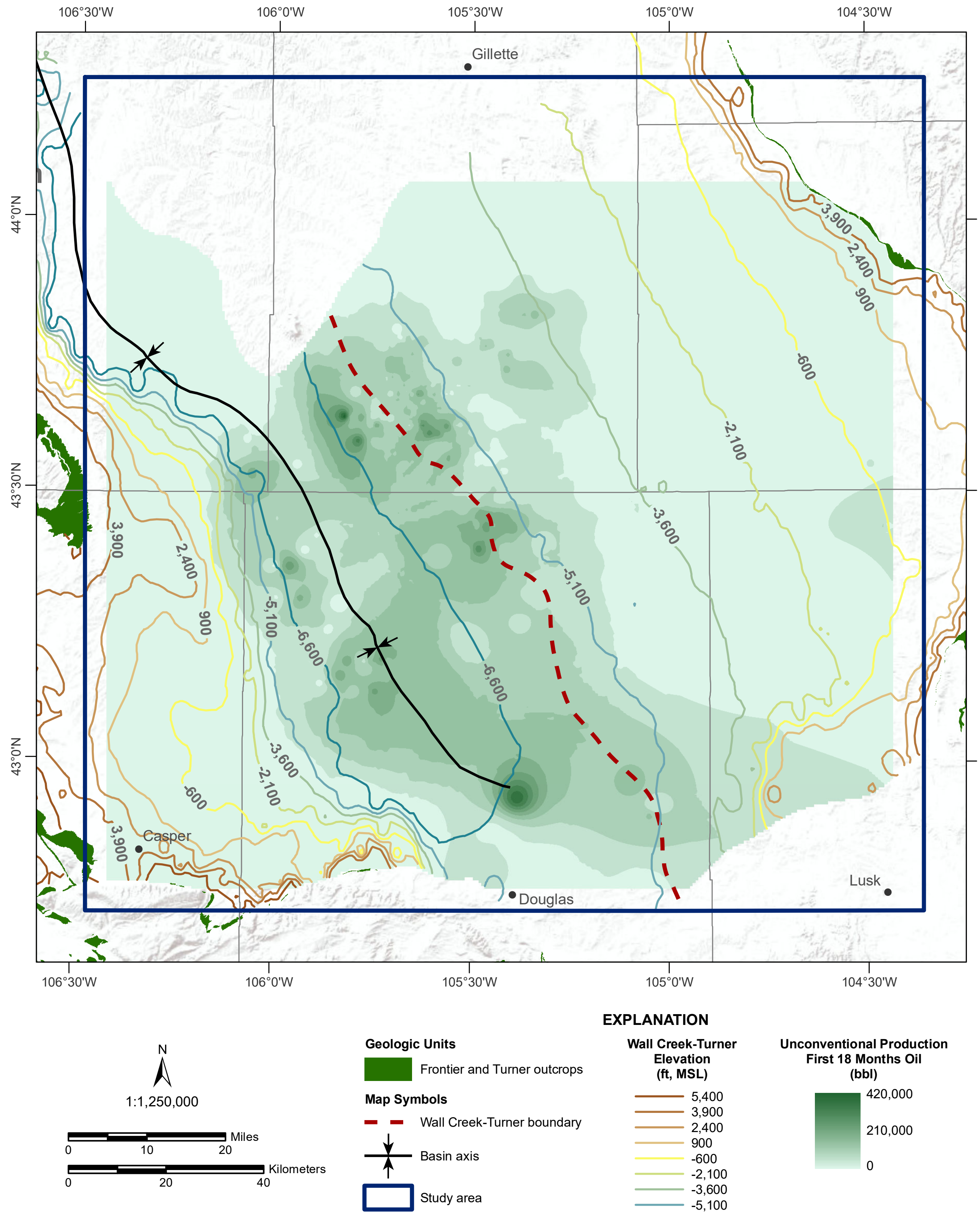

Figure 17. Top of Wall Creek and Turner sandstones (depth below mean sea level [MSL]) structure contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

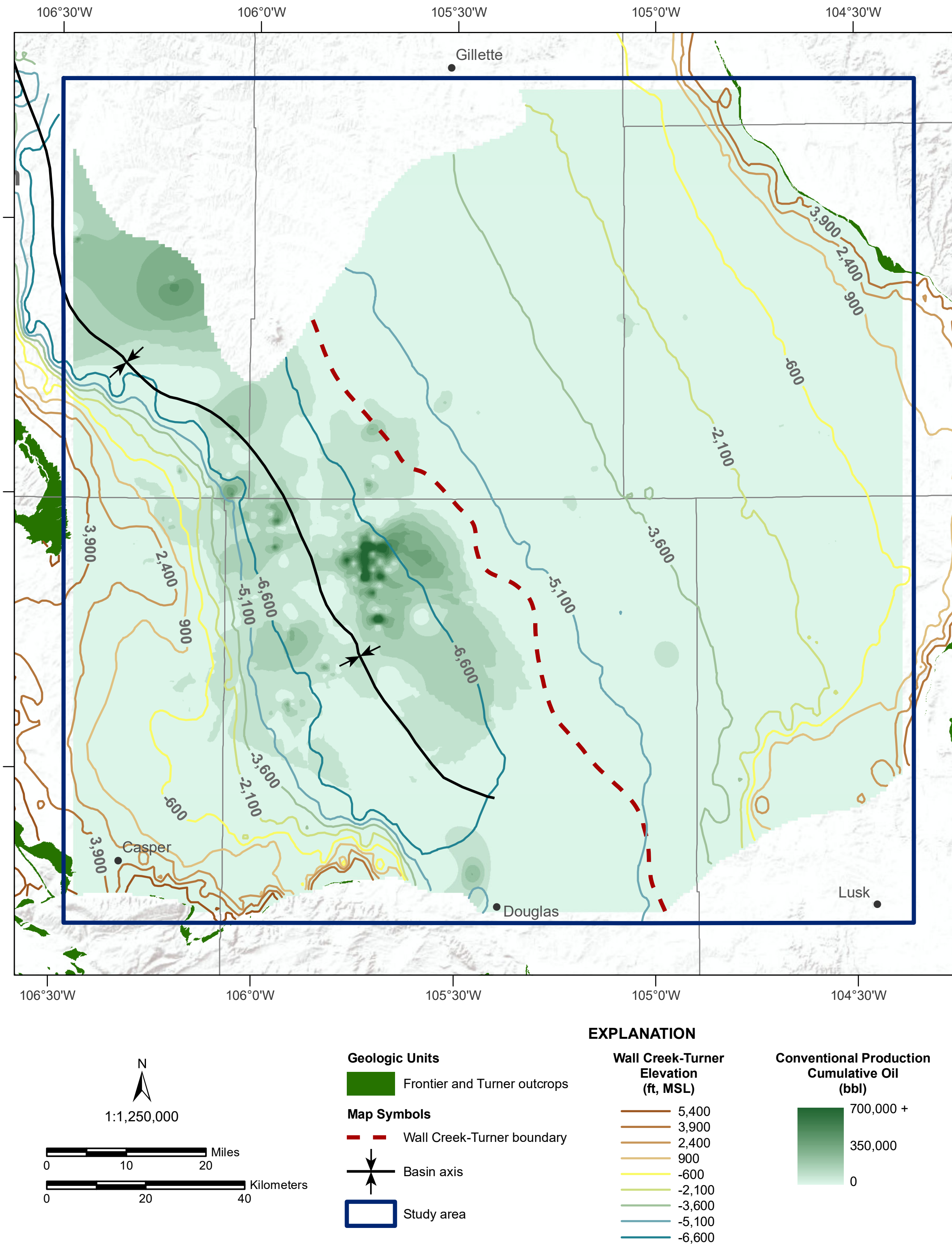

Figure 18. Top of Wall Creek and Turner sandstones (depth below mean sea level [MSL]) structure contours and cumulative conventional oil production from the Wall Creek-Turner reservoir.

Figure 19. Horizontal well total vertical depth versus first 18 months of unconventional oil (top row) and gas (bottom row) production. Vertical depth refers to the depth reported on directional surveys or completion reports at each horizontal well's bottom-hole location. Wall Creek wells are in the left column and symbolized by squares; Turner wells are in the right column and symbolized by circles. Wells are colored by operator. Operators not displayed on graphs do not have wells with 18 months of production.

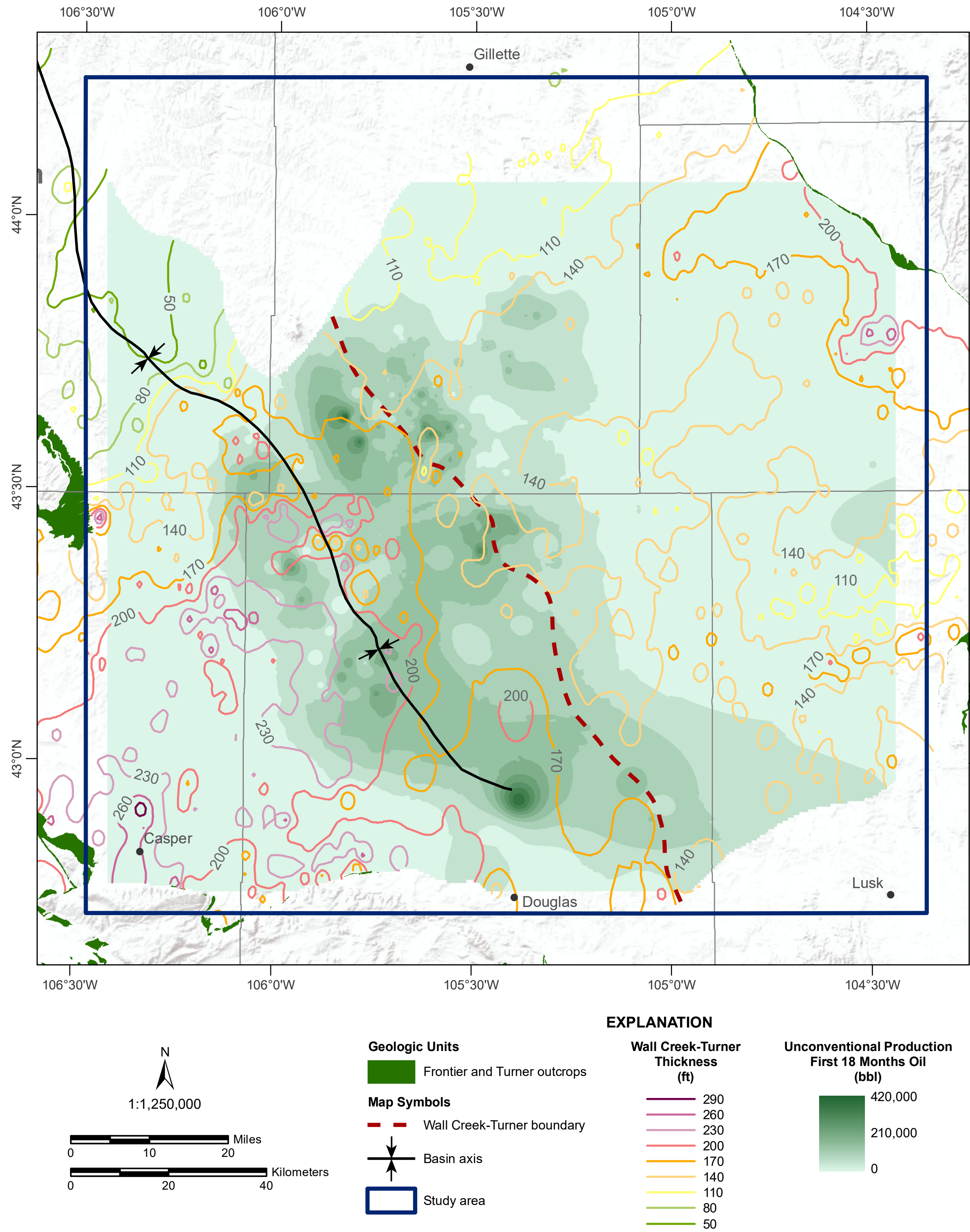

Figure 20. Wall Creek and Turner sandstone thickness (isochore) contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

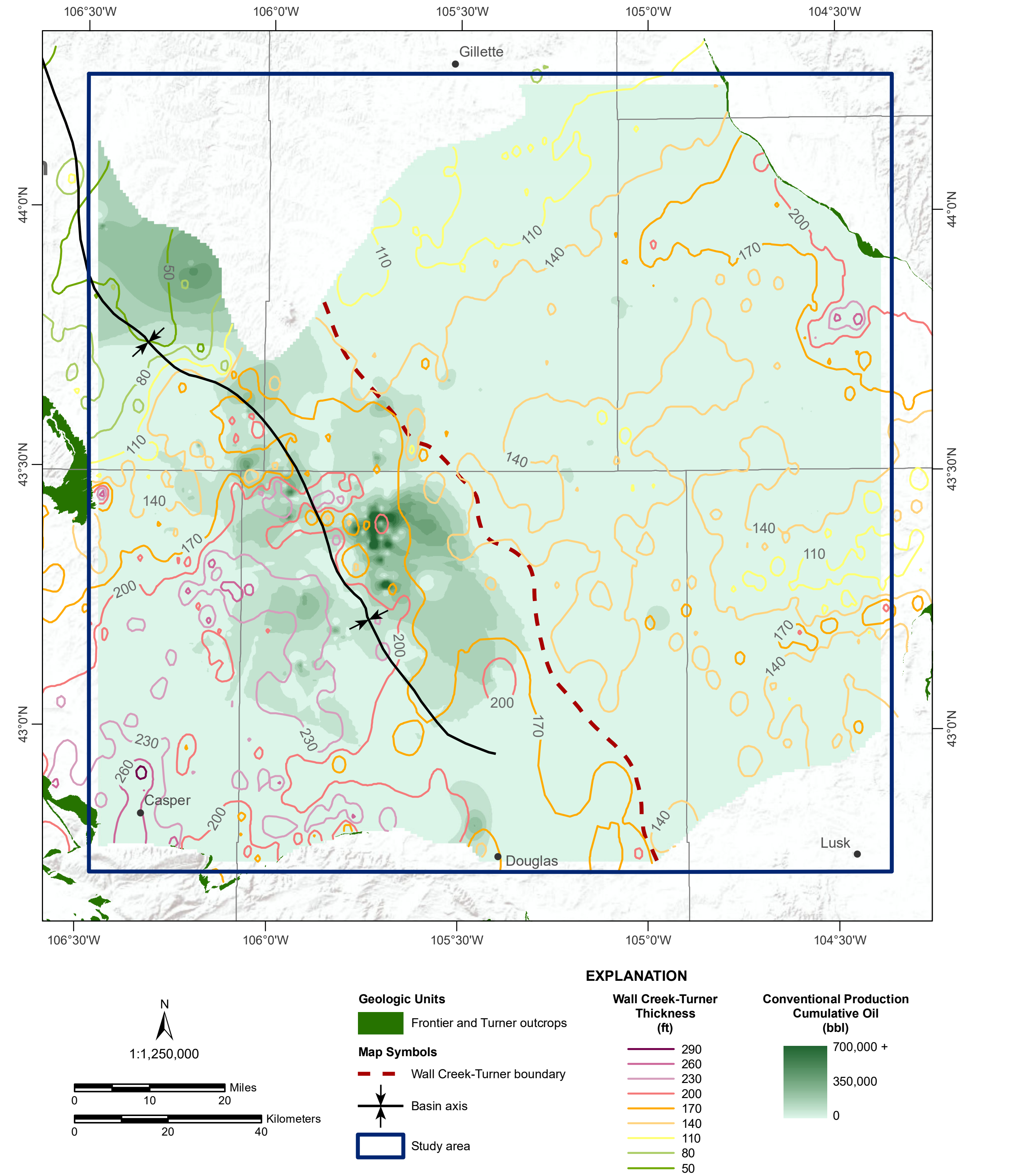

Figure 21. Wall Creek and Turner sandstone thickness (isochore) contours and cumulative conventional oil production from the Wall Creek-Turner reservoir.

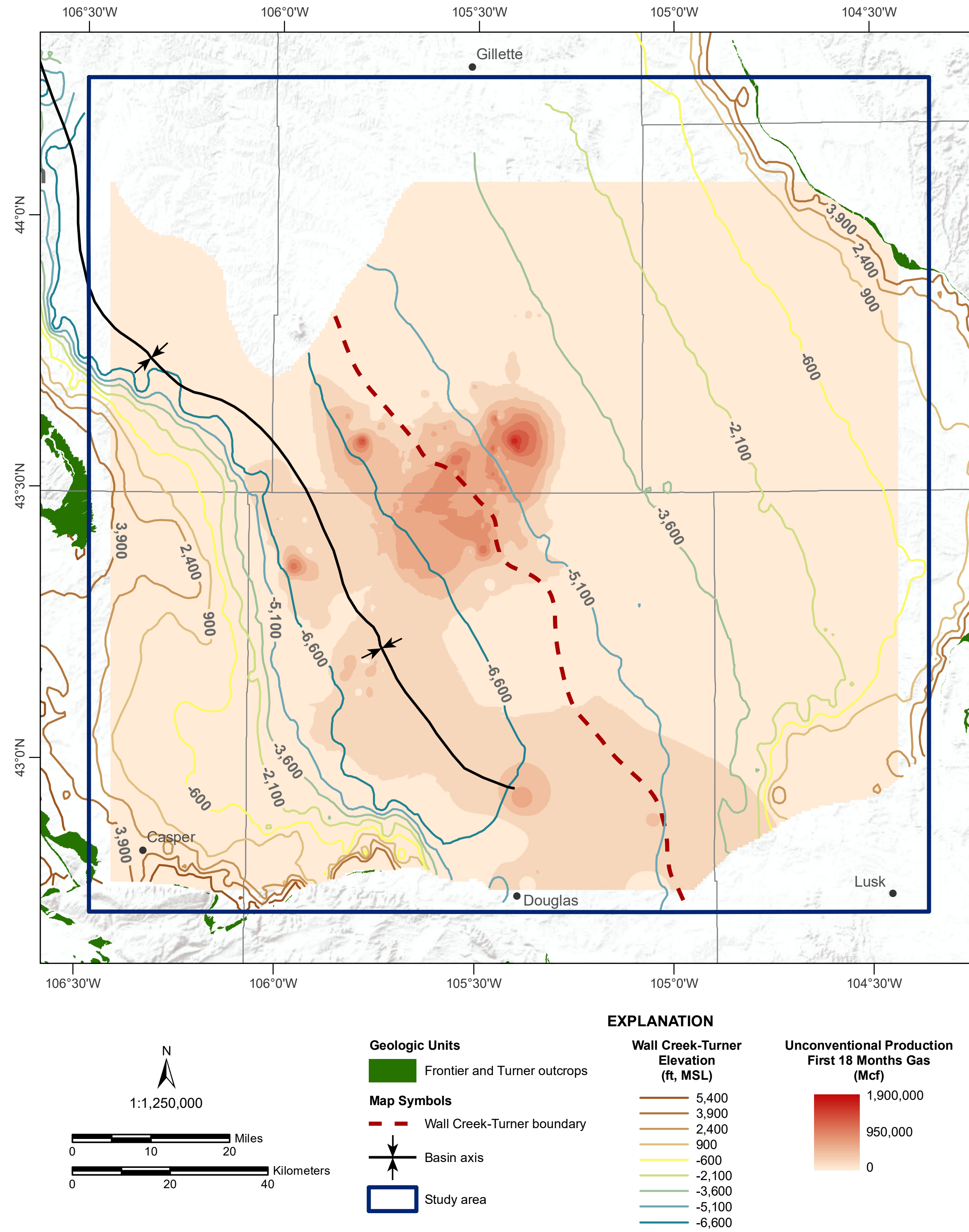

Figure 22. Top of Wall Creek and Turner sandstones (depth below mean sea level [MSL]) structure contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

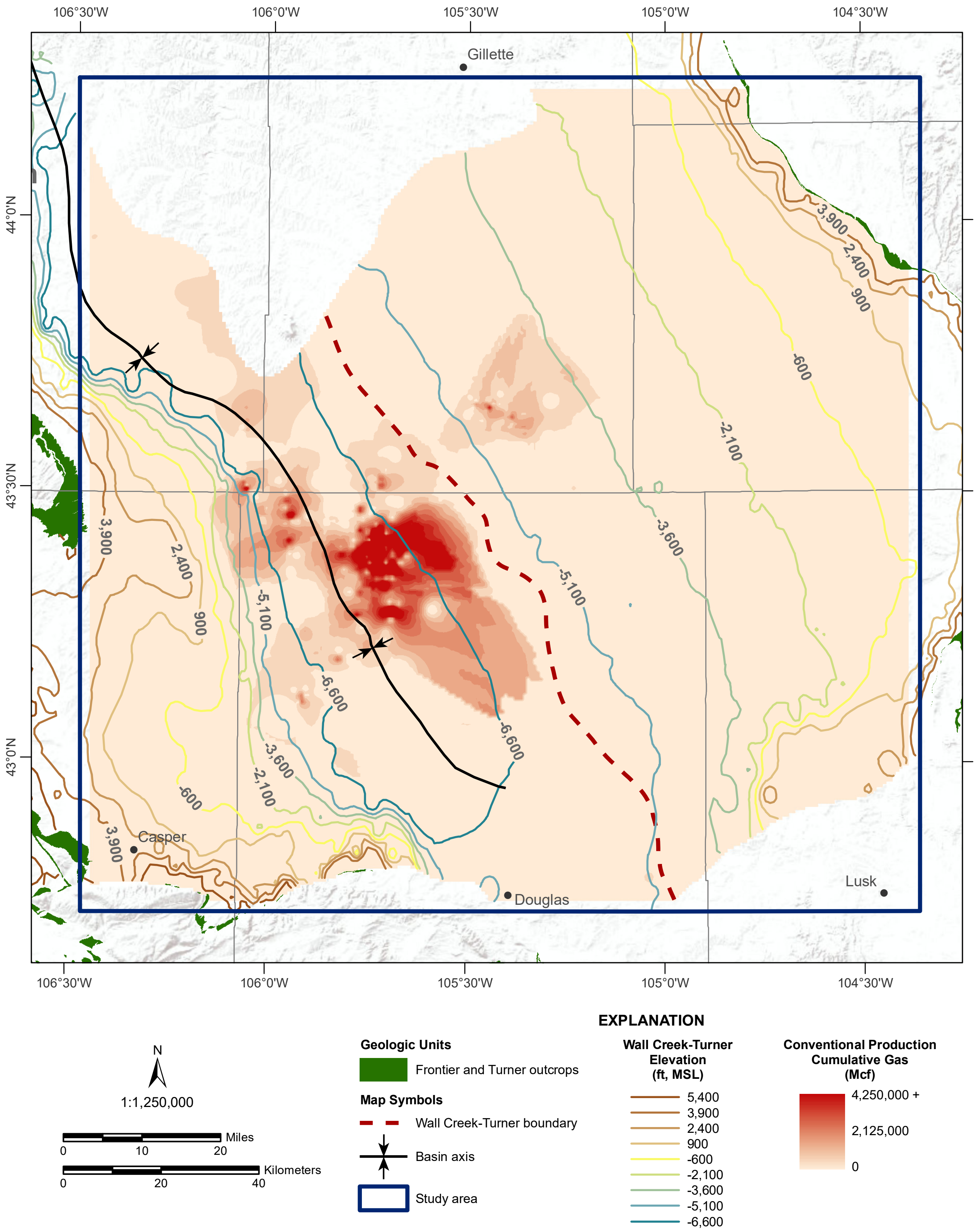

Figure 23. Top of Wall Creek and Turner sandstones (depth below mean sea level [MSL]) structure contours and cumulative conventional gas production from the Wall Creek-Turner reservoir.

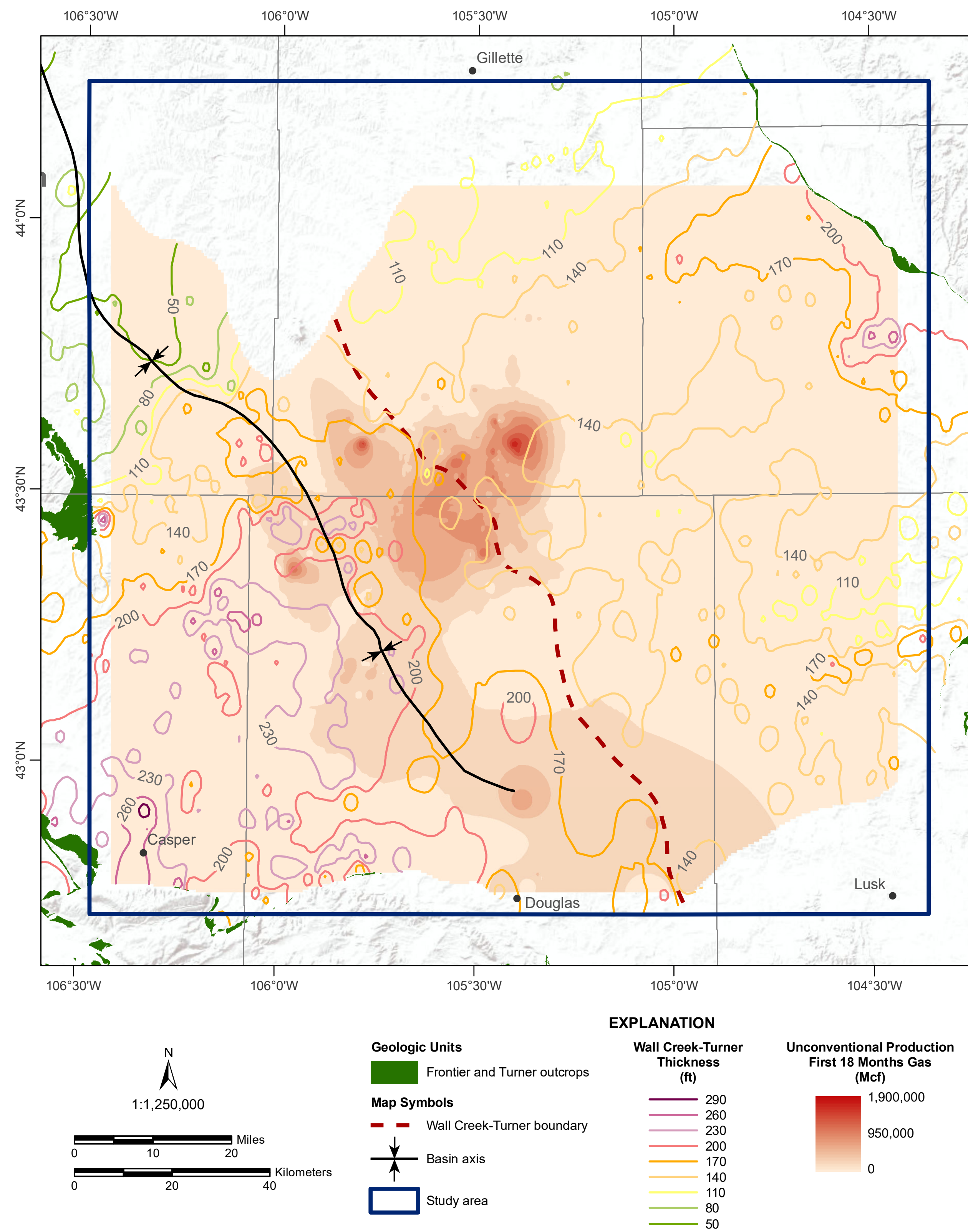

Figure 24. Wall Creek and Turner sandstone thickness (isochore) contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

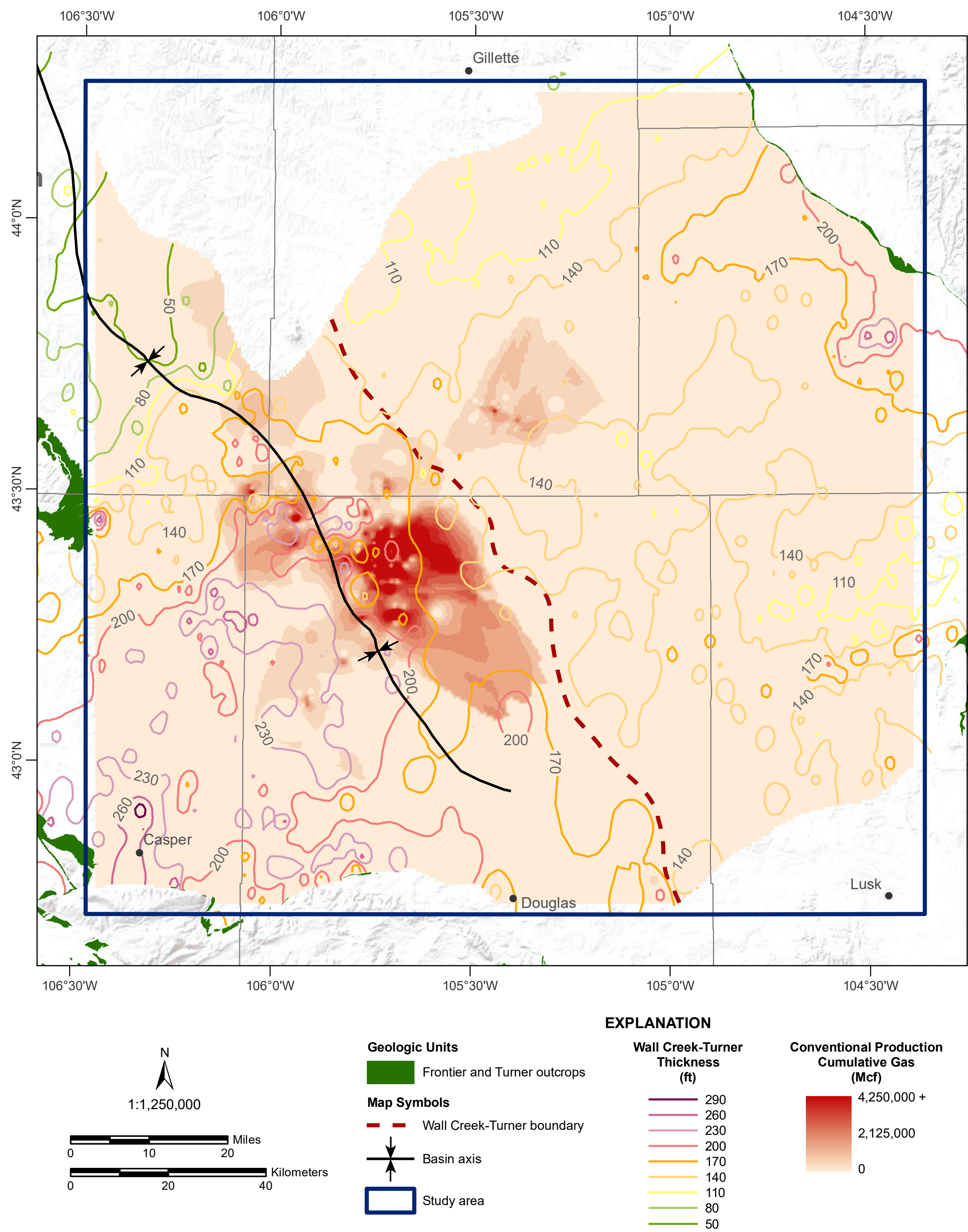

Figure 25. Wall Creek and Turner sandstone thickness (isochore) contours and cumulative conventional gas production from the Wall Creek-Turner reservoir.

Gas-Oil Ratios

Because oil is the primary target of most operators in the PRB, gas-oil ratios can provide insight as to the most favorable locations for oil production without excess associated gas. Wall Creek and Turner initial GOR were compiled from vertical and horizontal well initial production test data reported by WOGCC and IHS. For wells reporting only initial production oil and gas volumes (IP_{oil}, in bbl; IP_{gas}, in Mcf), GOR were calculated using the formula (IP_{gas}*1,000)/ IP_{oil} in ft^3/bbl. Reported GOR were corrected for any unit or calculation method inconsistencies, and multiple GOR for the same well were averaged. A total of 1,043 wells in the study area were used to generate the GOR surface and contour lines.

The resulting GOR interpolation shows high GOR areas near the basin margins and in a NE–SW trend through the middle of the study area that includes both Wall Creek and Turner wells (figs. 26 and 27). Comparing the GOR contours to horizontal wells' first 18 months of oil and gas production shows that most areas of high oil production border but fall outside the highest GOR contours. Predictably, the areas of highest GOR correspond to the high gas production region in southern Campbell County. These spatial trends are reinforced by the R values in table 5, which show weak-to-absent correlation of GOR with oil production, but moderate positive correlation with gas production. The GOR interpolated contours also indicate where additional areas of high gas production may be encountered during future development of the Wall Creek and Turner reservoirs.

Table 5. Statistical correlation between Wall Creek-Turner unconventional oil and gas production surfaces and reservoir gas-oil ratio surface.

Wall Creek-Turner product	R value (GOR)
unconventional first 18 months oil	0.09
unconventional first 18 months gas	0.39

Oil API Gravity

To further evaluate the oil composition being produced from the PRB Wall Creek and Turner reservoirs, the initial crude oil API gravities from 376 horizontal and 242 conventional wells throughout the basin were interpolated and contoured (figs. 28 and 29). Almost all Wall Creek-Turner oil produced within the study area have API gravities greater than 31.1° and can be categorized as light crude. Areas of extremely light oils (API gravities greater than 45°) are located near the southern edge of the basin and also in a NE–SW-trending swath through southern Campbell and northern Converse counties, spanning both Wall Creek and Turner wells.

Figures 28 and 29 show that most Wall Creek-Turner unconventional oil production is from portions of the basin with API gravities less than 50°. However, gas production from the reservoirs is highest in areas where API gravities are greater than 45°. API gravity has a statistically strong positive correlation with both oil and gas production from the Wall Creek and Turner (table 6).

The NE–SW trend of high API gravities also coincides spatially with areas of high GOR, confirming the presence of both lighter oil and higher gas fractions within this area. Areas as-yet undeveloped by unconventional practices but within the high GOR and API gravity contours may yield similar high gas production.

Table 6. Statistical correlation between Wall Creek-Turner unconventional oil and gas production surfaces and reservoir oil API gravity surface.

Wall Creek-Turner product	R value (API gravity)
unconventional first 18 months oil	0.83
unconventional first 18 months gas	0.89

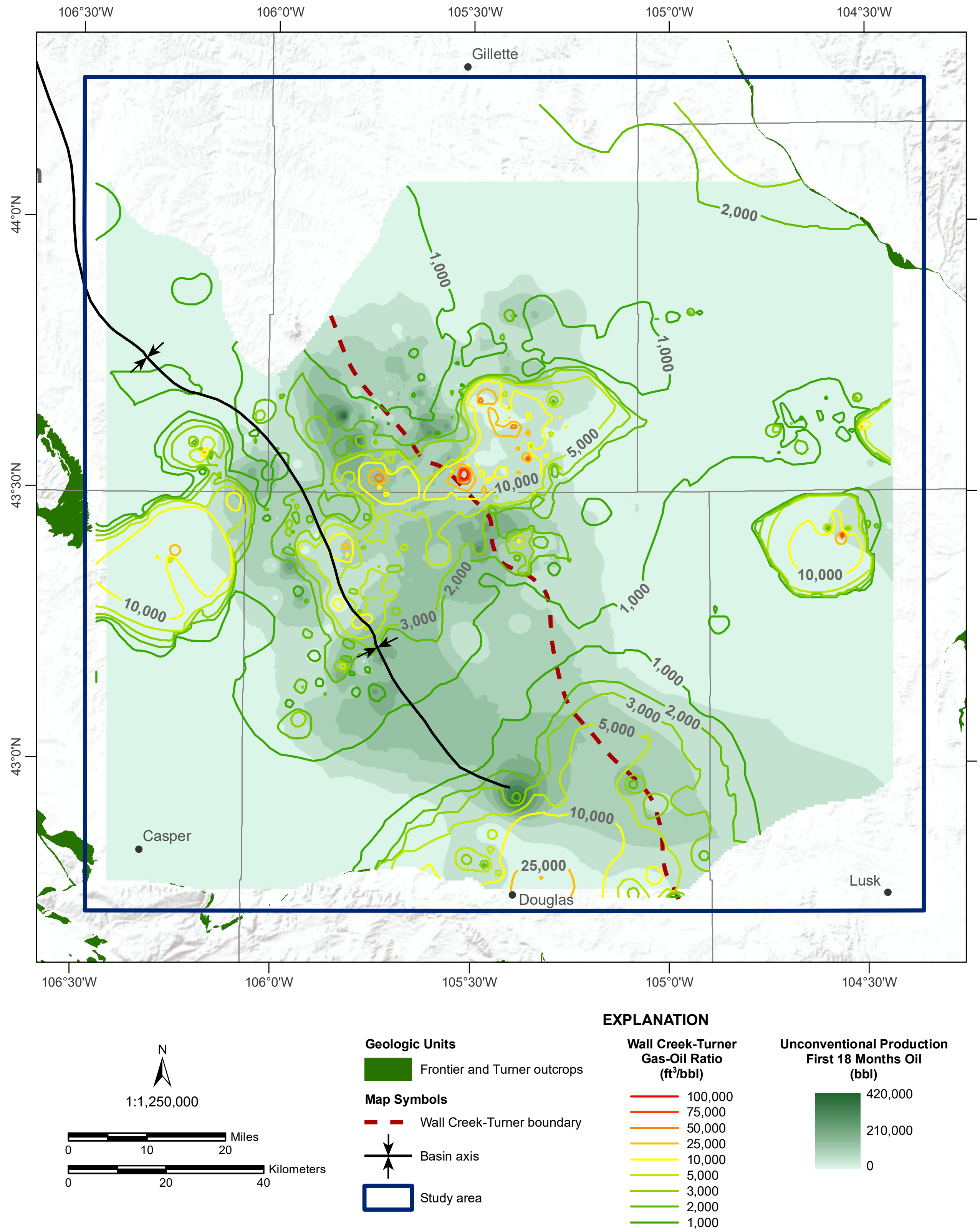

Figure 26. Gas-oil ratio contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

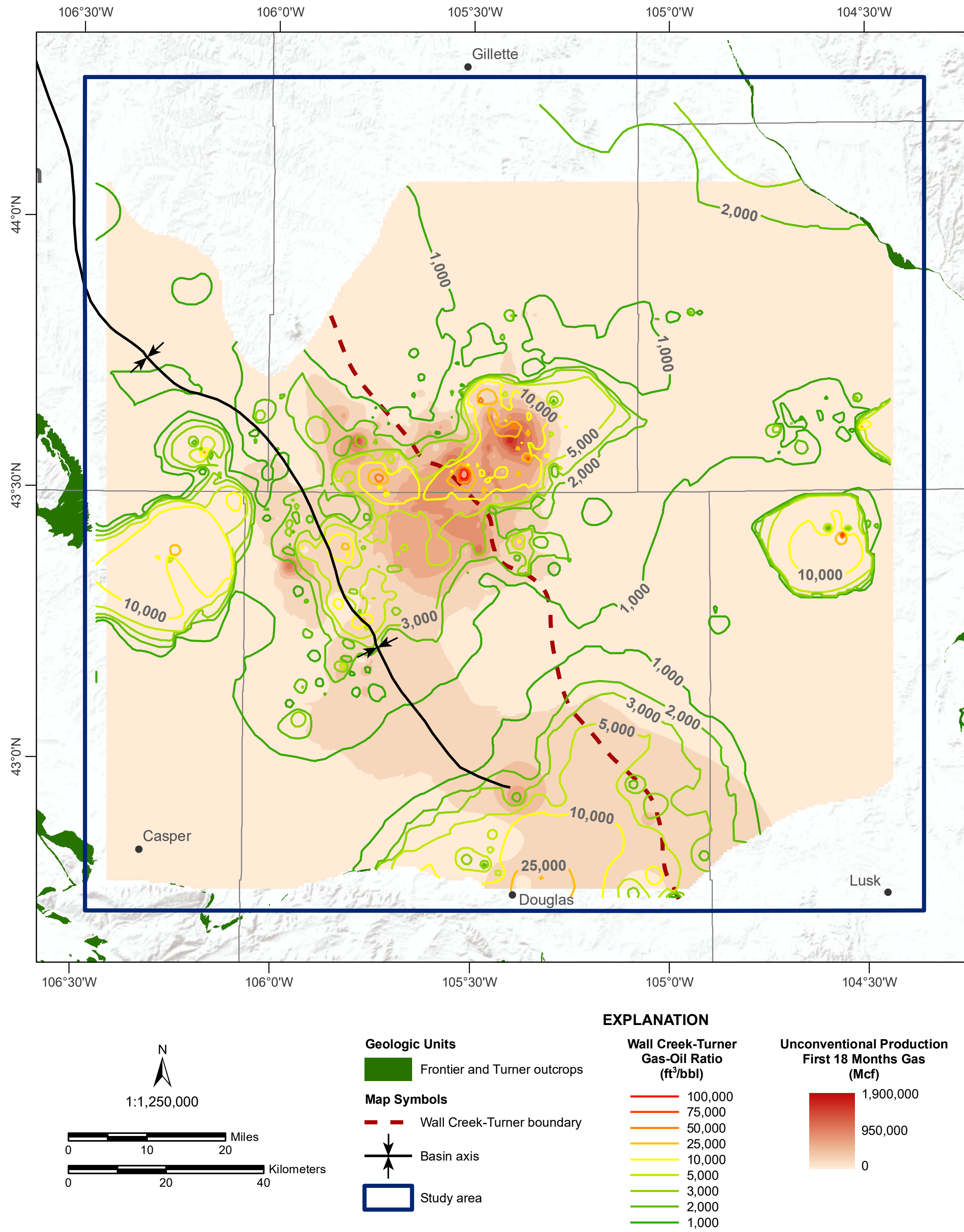

Figure 27. Gas-oil ratio contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

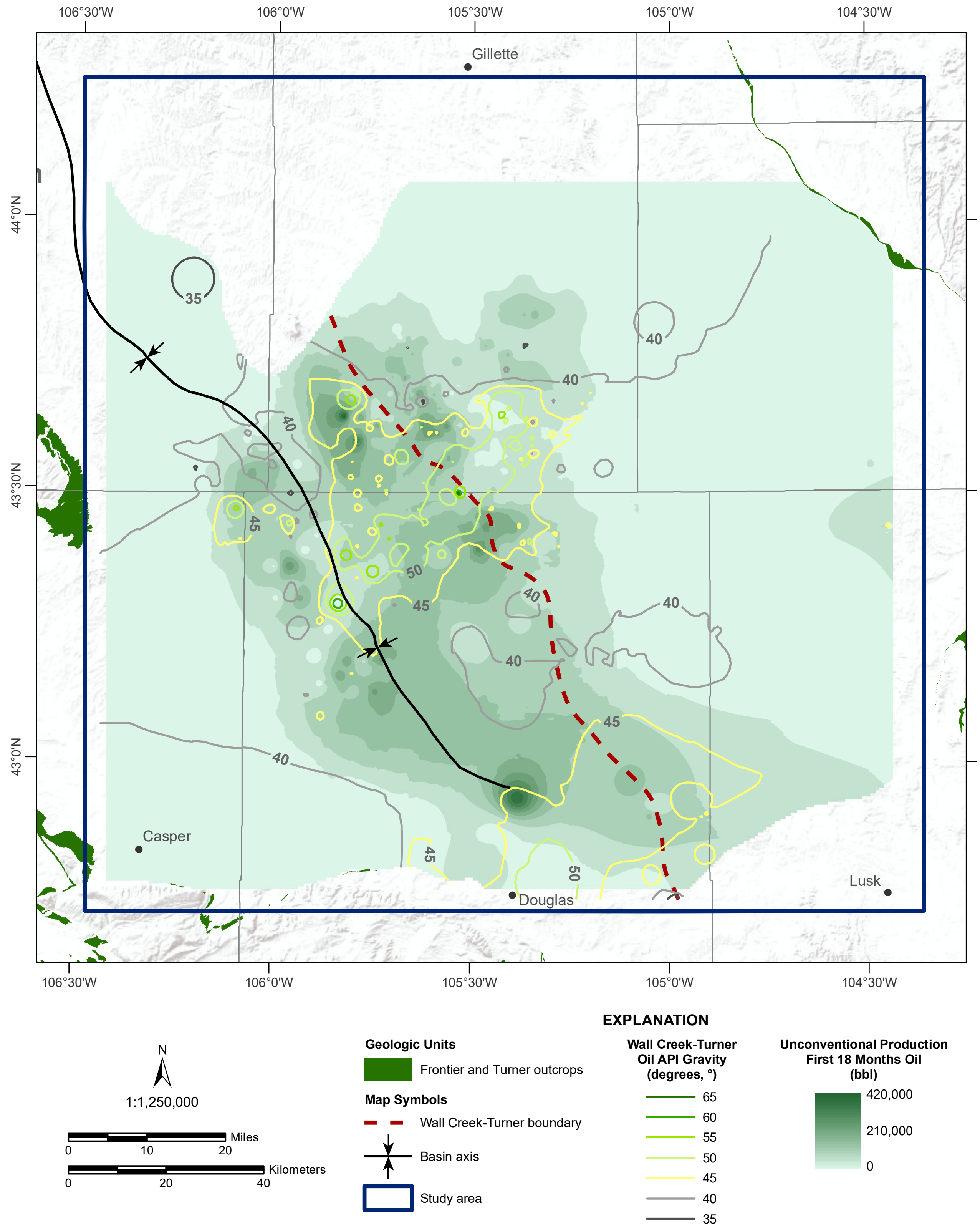

Figure 28. Crude oil API gravity contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

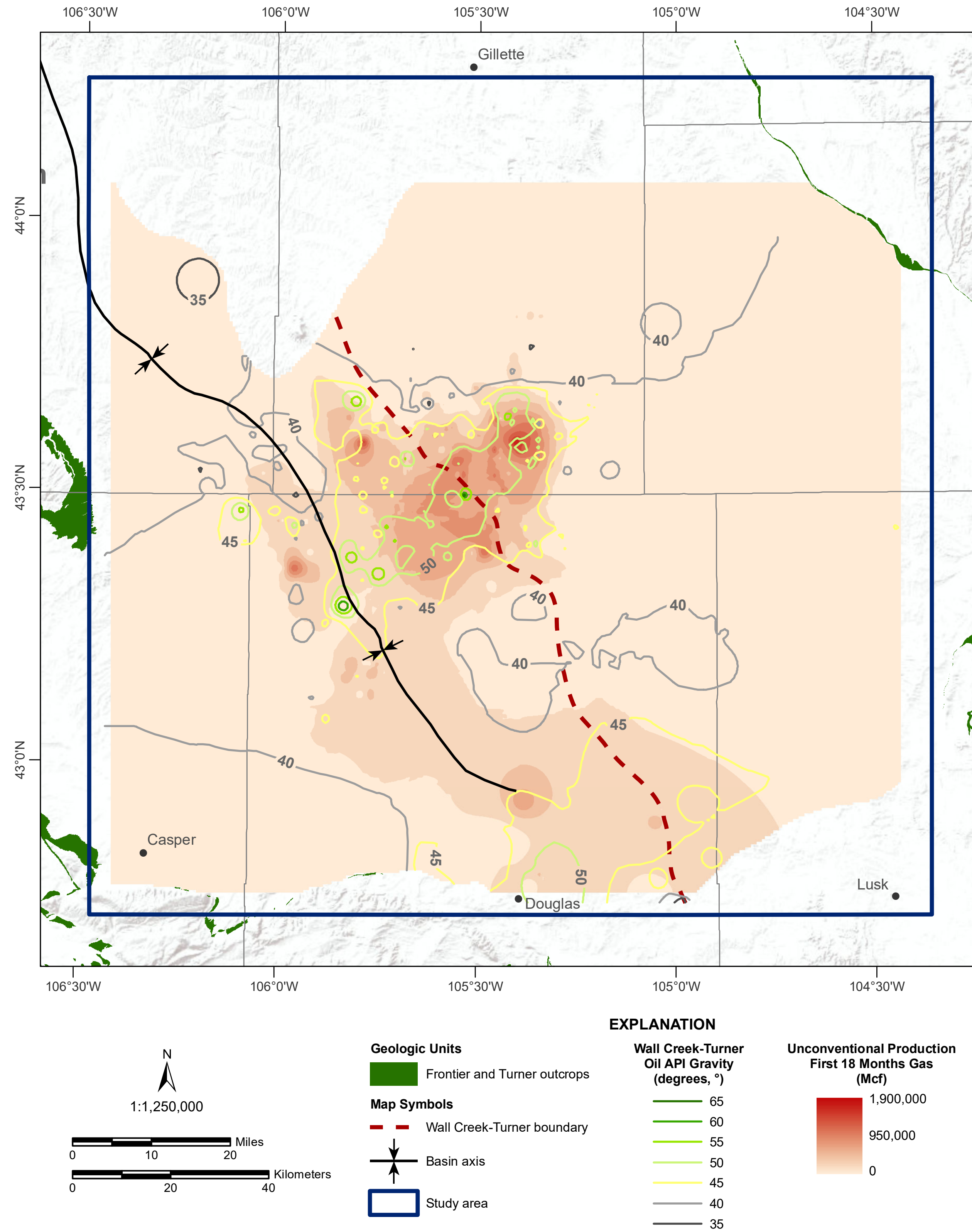

Figure 29. Crude oil API gravity contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

Natural Gas Composition

To document the natural gas composition produced from the PRB Wall Creek and Turner, natural gas C_1–C_5 fractions were compiled from WOGCC gas analysis reports and the U.S. Geological Survey's Energy Resources Program Energy Geochemistry database. Several authors have demonstrated that natural gas hydrocarbon fractions, specifically, *iso*-butane/*n*-butane (iC_4/nC_4) and gas wetness/dryness ratios, can be used to evaluate thermal maturity and possible gas migration pathways, respectively (Prinzhofer and others, 2000; Zumberge and others, 2012; Wood and Sanei, 2016). Thermal maturity (iC_4/nC_4) and gas dryness ($C_1/\sum C_1$–C_5) ratios were therefore calculated for 108 gas analyses from 86 wells to determine if they can explain PRB Wall Creek and Turner natural gas production trends (Appendix 1).

The majority (87 percent) of Wall Creek-Turner gas analyses in the study area have iC_4/nC_4 ratios between 0.25 and 0.50 (fig. 30), suggesting a similar thermal maturity throughout the reservoirs. Higher iC_4/nC_4 ratios are present east and south of the main well group, with the highest ratios from two wells north of the high gas production area. However, these higher iC_4/nC_4 ratios from more mature hydrocarbons are surrounded by less mature gases with lower iC_4/nC_4 ratio analyses.

To identify potential migration pathways indicated by preferential methane enrichment, Wall Creek-Turner natural gas dryness ratios are plotted in figure 31. Higher methane fractions are common throughout the study area, with an average ratio of 0.73. Turner wells in the shallower eastern portion of the basin exhibit a larger range of dryness ratios than the deeper Wall Creek wells. Although not consistent, it is possible the higher dryness ratios east of the basin axis suggest some migration out of the deeper portions of the reservoir.

The range of butane and methane ratios from the available natural gas analyses suggest a complex hydrocarbon system for the Wall Creek and Turner reservoirs. It appears that there is some variation in source rock thermal maturity and that the resulting natural gas has potentially undergone limited secondary migration. Consistent spatial trends could not be definitively identified by this study, in part due to the limited dataset.

Regional Basin Tectonics

Multiple regional lineaments identified from satellite imagery, gravity surveys, and stratigraphic thickness anomalies transect the Powder River Basin. Several authors interpret these linear features as surficial expressions of Precambrian basement faults and propose that continued movement along the faults controlled the distribution of Upper Cretaceous reservoirs (Slack, 1981; Marrs and Raines, 1984; Weimer and Flexer, 1985; Mitchell and Rogers, 1993; Anna, 2010). Slack (1981) specifically notes that Turner deposits near the Black Hills parallel the Belle Fourche Arch lineaments and align with older reservoir (Muddy Sandstone) deposition trends. Marrs and Raines (1984) suggest that both their northeast-trending lineaments—which may be extensions of Slack's trends—and their northwest-trending lineaments could have influenced sediment deposition patterns and subsequent hydrocarbon accumulation in PRB reservoirs.

To broadly evaluate whether regional tectonics influenced the Wall Creek and Turner reservoir geometry, horizontal wells' first 18 months of production was overlain by regional lineaments from Slack (1981), Marrs and Raines (1984), Anna (1986, 2010) and Maughan and Perry (1986; figs. 32 and 33). Conventionally named oil and gas fields with wells producing from the Frontier, Wall Creek, Carlile, or Turner reservoirs (Toner and others, 2018) are also included on these figures. Although the oil and gas fields do not include horizontal wildcat wells that also produce from the Wall Creek or Turner reservoirs, their geometries do generally parallel the northwest-southeast lineaments, especially along and west of the basin axis. Unconventional oil and gas production also appears bracketed by the lineaments, with the NE–SW-trending lineaments and those identified by Marrs and Raines (1984) forming noticeable boundaries between areas of highest production.

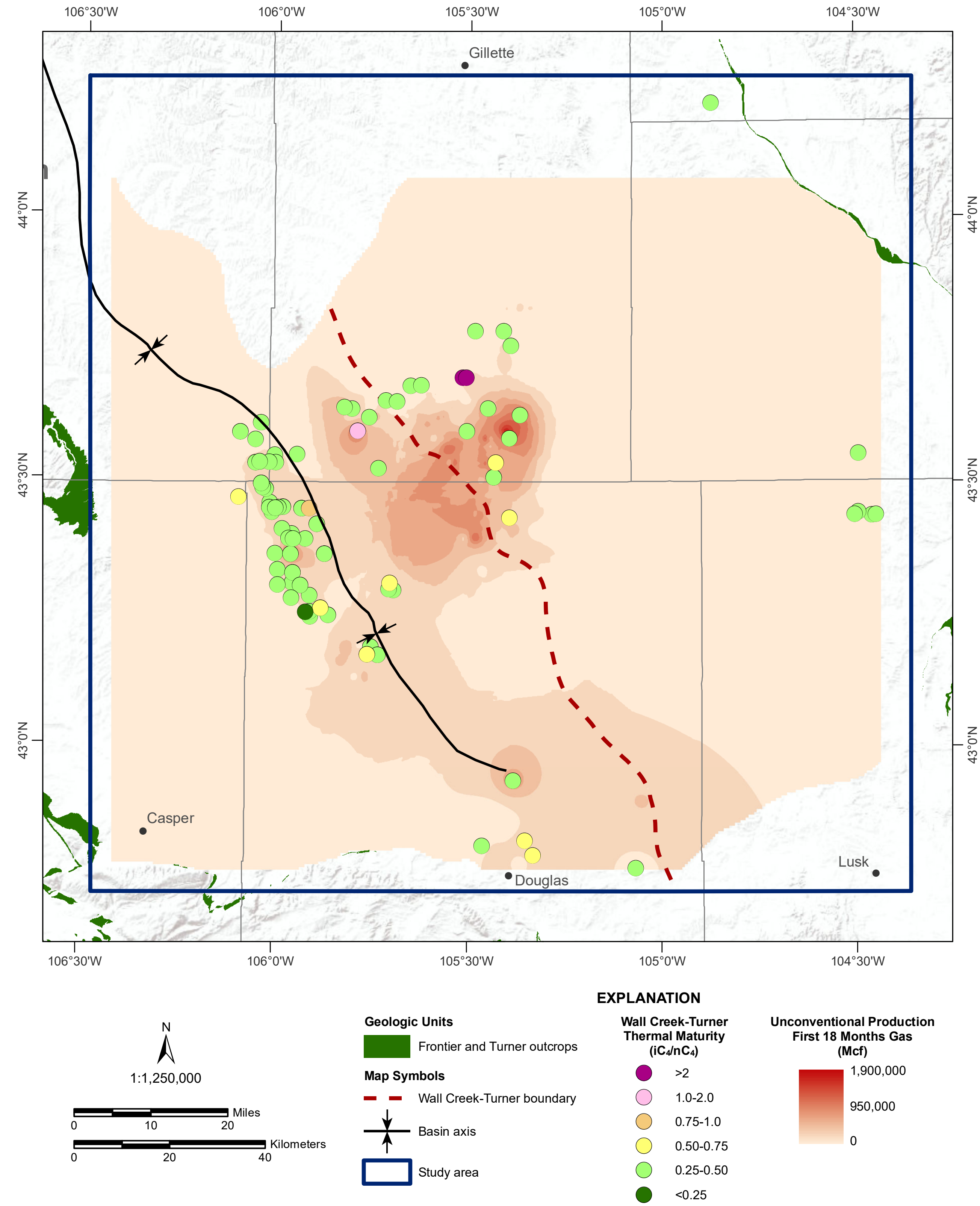

Figure 30. Natural gas *iso*-butane/*n*-butane ratios (iC_4/nC_4) and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

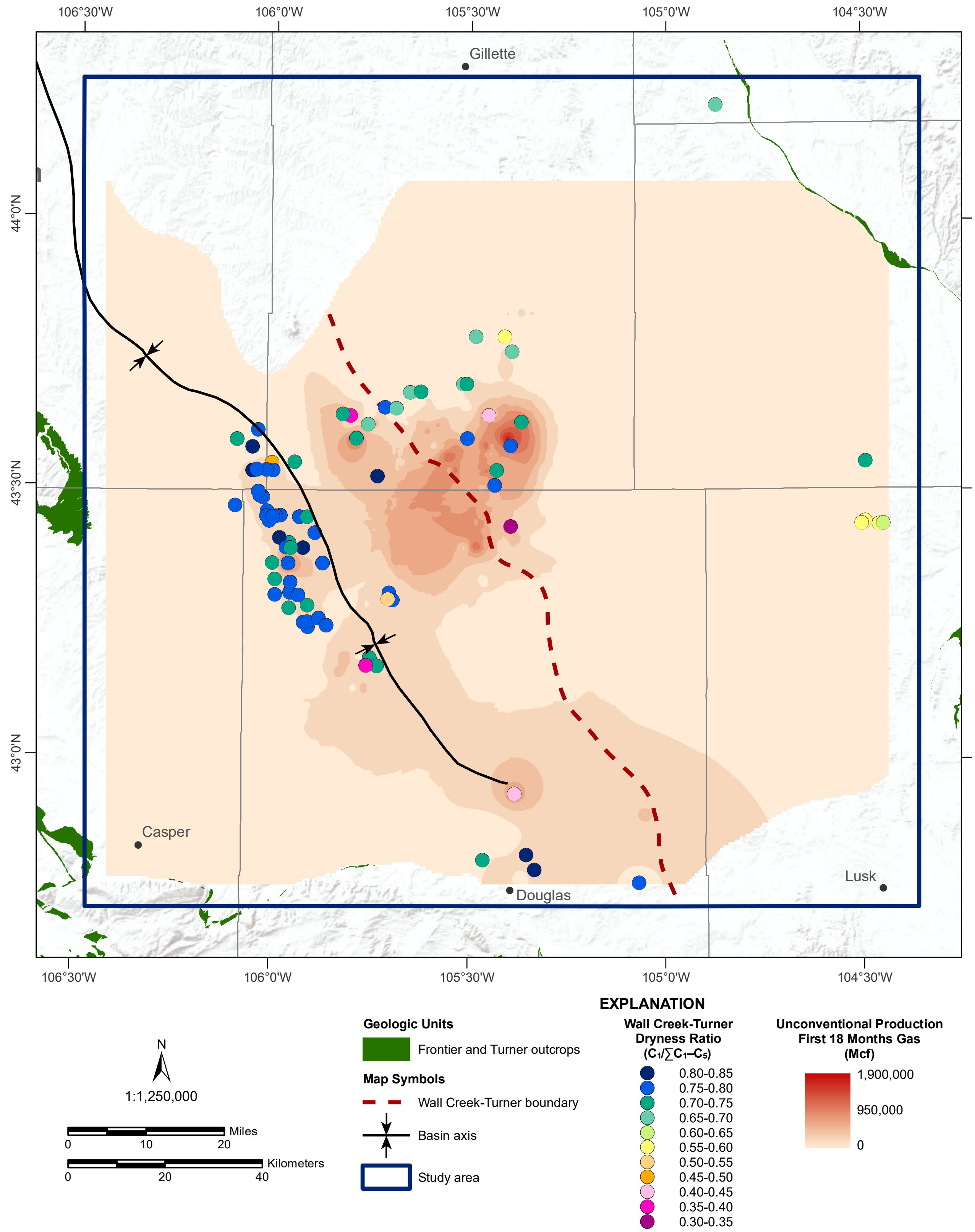

Figure 31. Natural gas dryness ratios ($C_1/\sum C_1$–C_5) and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

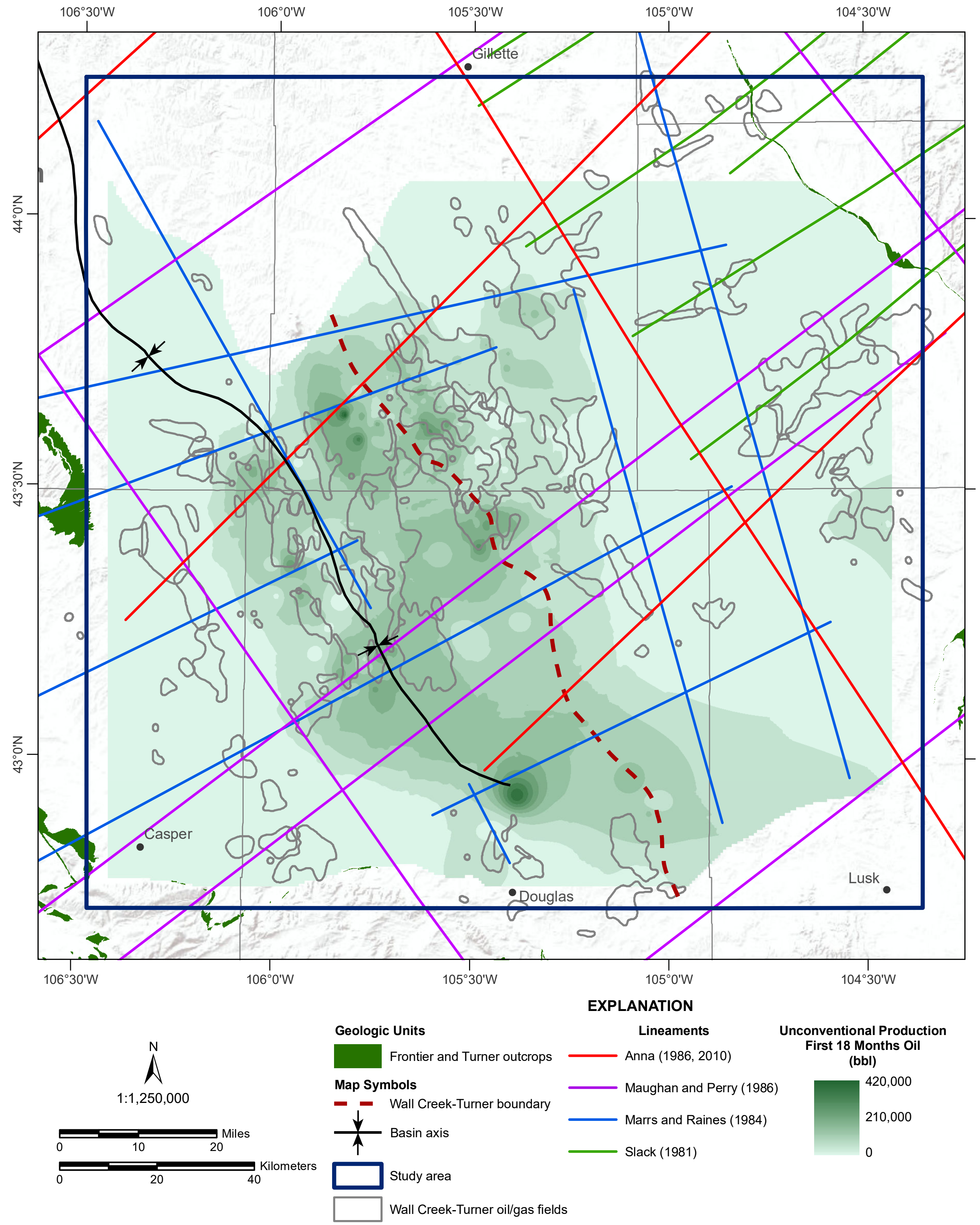

Figure 32. Regional lineaments and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir. Outlines of Frontier-, Wall Creek-, Carlile-, and Turner-producing oil and natural gas fields are shown for reference.

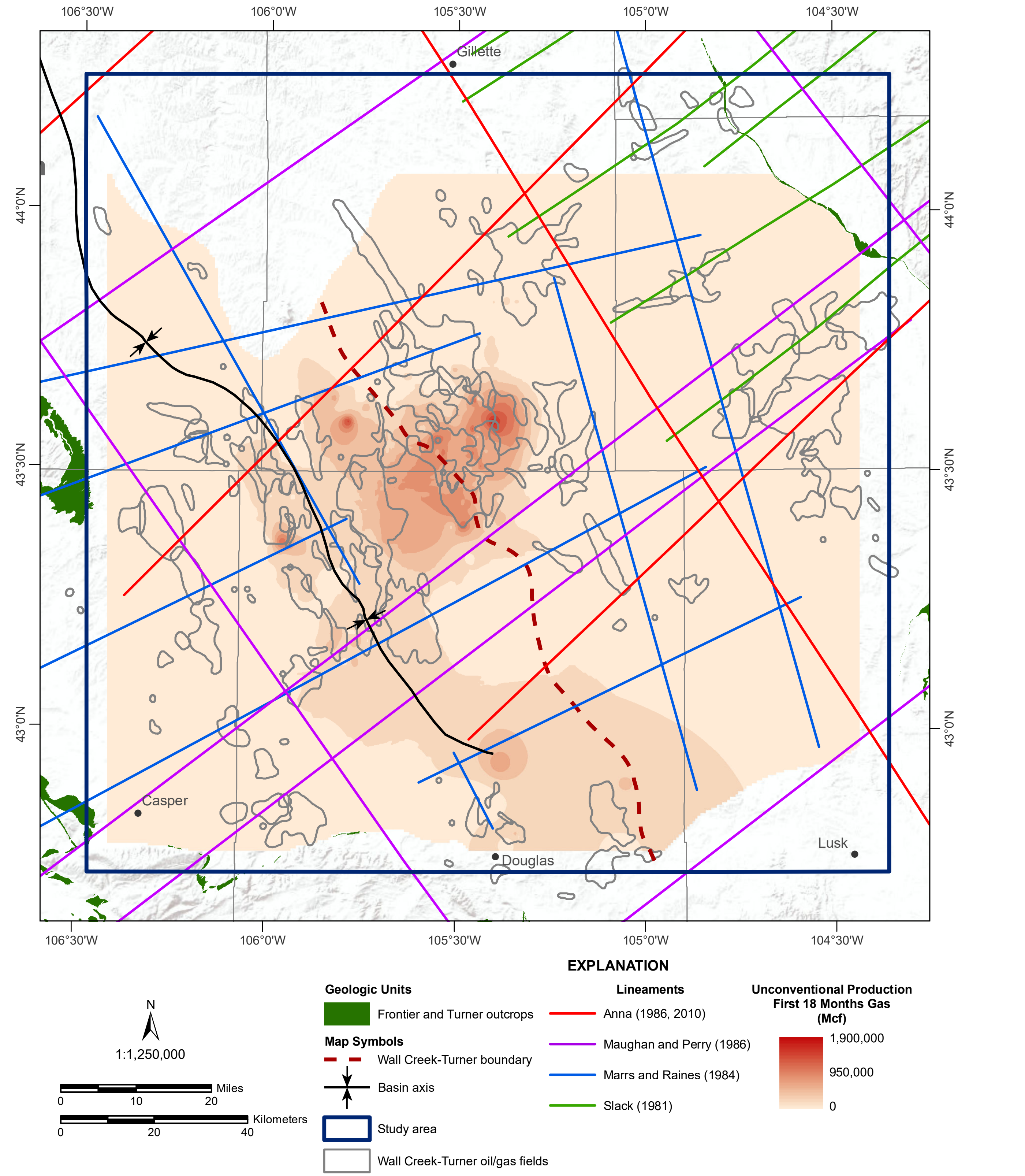

Figure 33. Regional lineaments and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir. Outlines of Frontier-, Wall Creek-, Carlile-, and Turner-producing oil and natural gas fields are shown for reference.

Pressure

Because hydrocarbon production depends on reservoir pressure, the WOGCC database was researched to determine if drill stem tests (DST) existed for this study's horizontal Wall Creek-Turner wells. While no horizontal DST were publicly available, 14 horizontal gas wells producing from the Turner did have bottom-hole pressure test surveys, with repeated pressure tests available for three wells. EOG owns all 14 horizontal gas wells, which plot within the area of high gas production in southern Campbell County. Two of these wells (API numbers 49-005-60281 and 49-005-60885) also have associated fluid study reports focusing on gas condensate composition and reservoir pressure-volume-temperature analysis.

Despite continued debate over the exact definition, gas condensates are typically considered to have high API gravities (45°–75°), GOR ranges of 2,500–50,000, larger proportions of heavier hydrocarbon components than dry or wet gases, and present as a single-phase gas at original reservoir pressure-temperature conditions (Whitson, 1992; Whitson and Brule, 2000; PetroWiki, 2018). Condensates will separate into liquid and gas phases as reservoir pressure drops below the dew point in a process called retrograde condensation (fig. 34; Whitson, 1992; Lal, 2003; Fan and others, 2005). Retrograde condensation can affect well productivity as gas flow becomes choked off by the competing liquids. Injection of dry gas or additional artificial lift or pumping methods may become necessary to recover stranded condensate liquids (Fan and others, 2005). Pressure monitoring is critical to maintaining a gas-condensate reservoir's yield, and explains the repeated pressure tests in Campbell County's elevated gas production area.

Because no DST for horizontal Wall Creek-Turner wells were available, IHS' database was queried for vertical well DST. Initial shut-in pressure (ISIP) and final shut-in pressure (FSIP) from 620 PRB Wall Creek and Turner DST were compiled and evaluated (IHS, 2018). Close agreement between initial and final shut-in pressures is ideal, as it indicates that the test pressure reached formation pressure equilibrium (Heasler and others, 1994). When Wall Creek-Turner ISIP and FSIP are compared (fig. 35), despite

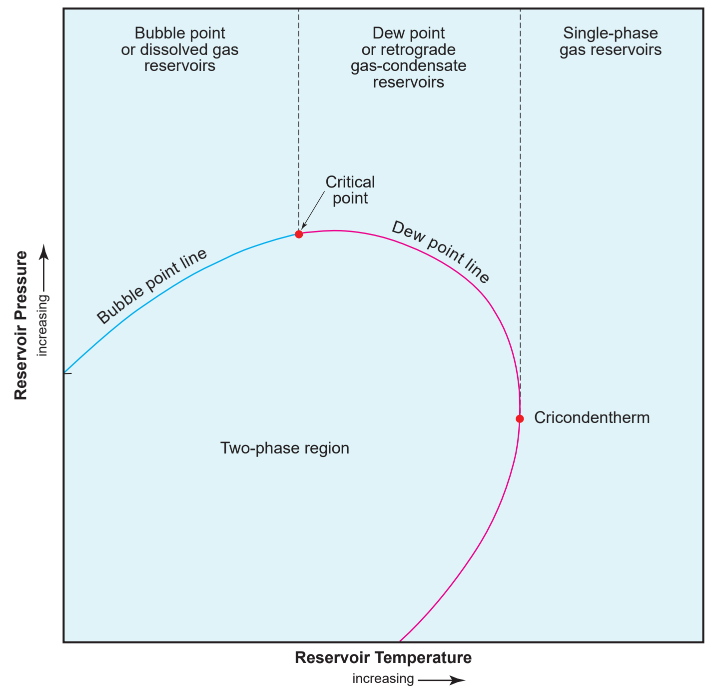

Figure 34. Schematic gas-condensate reservoir phase diagram. Gas condensate reservoirs exist as a single-phase reservoir at pressures above the dew point line and at temperatures between the critical point and the cricondentherm (the maximum temperature at which two phases can simultaneously occur in a gas-condensate reservoir). If pressure within a gas-condensate reservoir drops below the dewpoint, retrograde condensation occurs and reservoir fluids change from a single phase (gas) to two phases (gas and liquid). Modified from Terry and others, 2015.

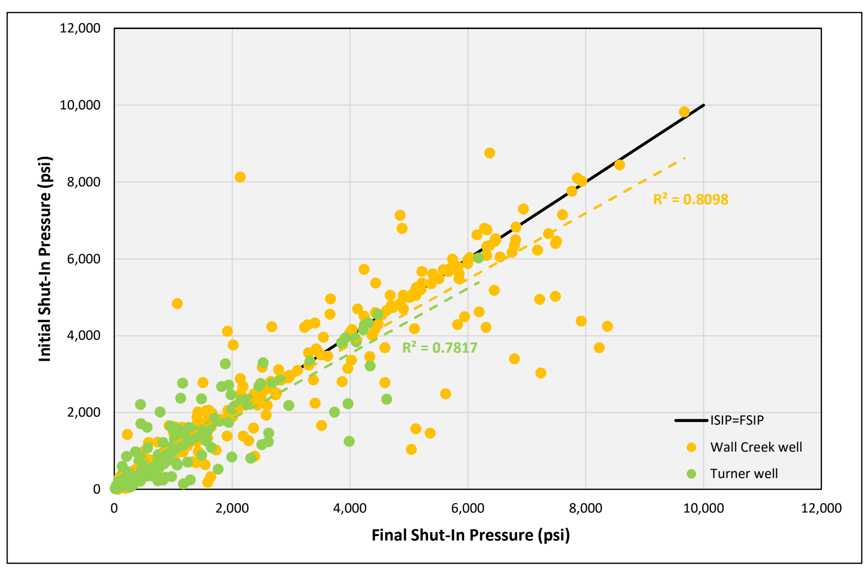

Figure 35. Wall Creek and Turner drill stem test intial shut-in pressures versus final shut-in pressures.

some scatter, 56 percent of the wells have an ISIP within 25 percent of their FSIP. This study follows Heasler and others' (1994) method of including all applicable DST in the dataset, but using the larger of the ISIP and FSIP for further analysis.

The Wall Creek-Turner maximum DST shut-in pressures (MSIP) are plotted by depth and compared to standard pressure gradients in figure 36. The measured depths (MD) used for this analysis are the averages of the reported DST top and bottom depths. Pressure gradients for Upper Cretaceous formations in the Powder River Basin are generally considered to be equivalent to freshwater at 0.433 pounds per square inch/foot (psi/ft), although Heasler and others (1994) note some drillers prefer to use a 0.465 psi/ft gradient, similar to Gulf Coast reservoirs. Many wells in the study area plot on or to the left of the pressure gradient lines, indicating either normal to underpressured reservoir conditions or that the DST was not run to completion. Both reservoirs do, however, exhibit overpressured conditions, with the number of overpressured Wall Creek wells increasing with depth.

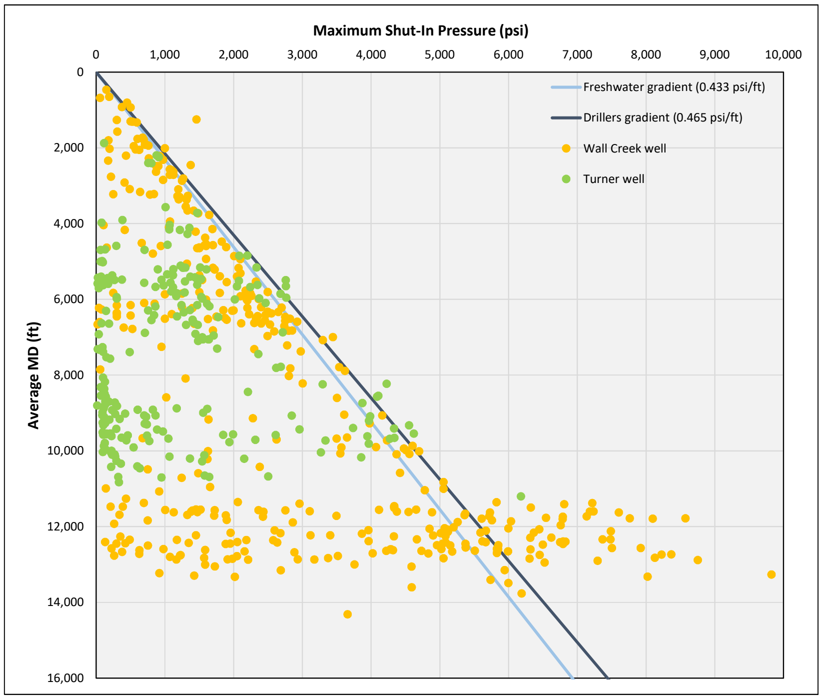

Figure 36. Wall Creek and Turner drill stem test maximum shut-in pressures plotted as a function of depth. Maximum shut-in pressure is the larger of either the drill stem test initial shut-in pressure or the final shut-in pressure. Reservoir overpressure increases at depths greater than 11,000 ft.

In order to identify the location of these overpressured wells, all DST pressures were converted to pressure gradient values (1/(depth/MSIP)) and contoured (figs. 37 and 38). The resulting contours show that the Wall Creek reservoir generally exhibits higher pressures than the Turner, in a trend straddling the deepest portion of the basin. However, several overpressured Turner wells are present in much shallower areas of the study area.

When these interpolated pressure gradients are compared to Wall Creek-Turner horizontal wells' first 18 months of production (figs. 37 and 38), in most cases the areas of highest oil and gas production do not spatially correspond with overpressured reservoir conditions. While this may in part be a construct of comparing vertical well pressure contours to horizontal well production, the DST locations do overlap and surround the horizontal wells, lending credence to using the vertical well DST interpolation to document whether reservoir pressure influences horizontal well production. Both Wall Creek and Turner oil and gas production have moderate negative correlations with pressure gradient (table 7), supporting the spatial observation that the highest production, so far, has not come from overpressured portions of the reservoir. As of the current dataset, reservoir pressure alone does not appear to be the driving factor behind horizontal well performance.

Table 7. Statistical correlation between Wall Creek-Turner unconventional oil and gas production surfaces and reservoir pressure gradient surface.

Wall Creek-Turner product	R value (pressure gradient)
unconventional first 18 months oil	-0.54
unconventional first 18 months gas	-0.35

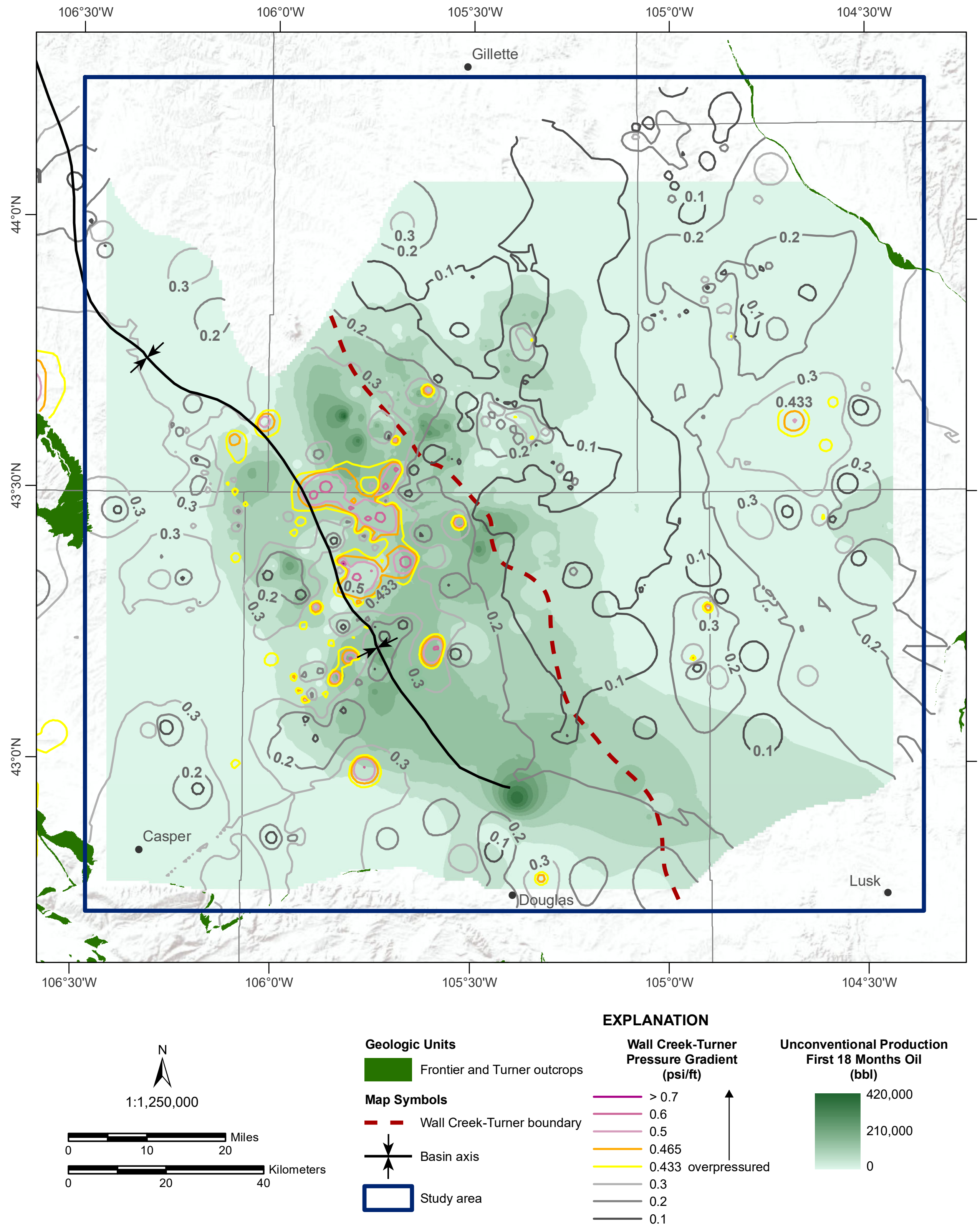

Figure 37. Pressure gradient contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

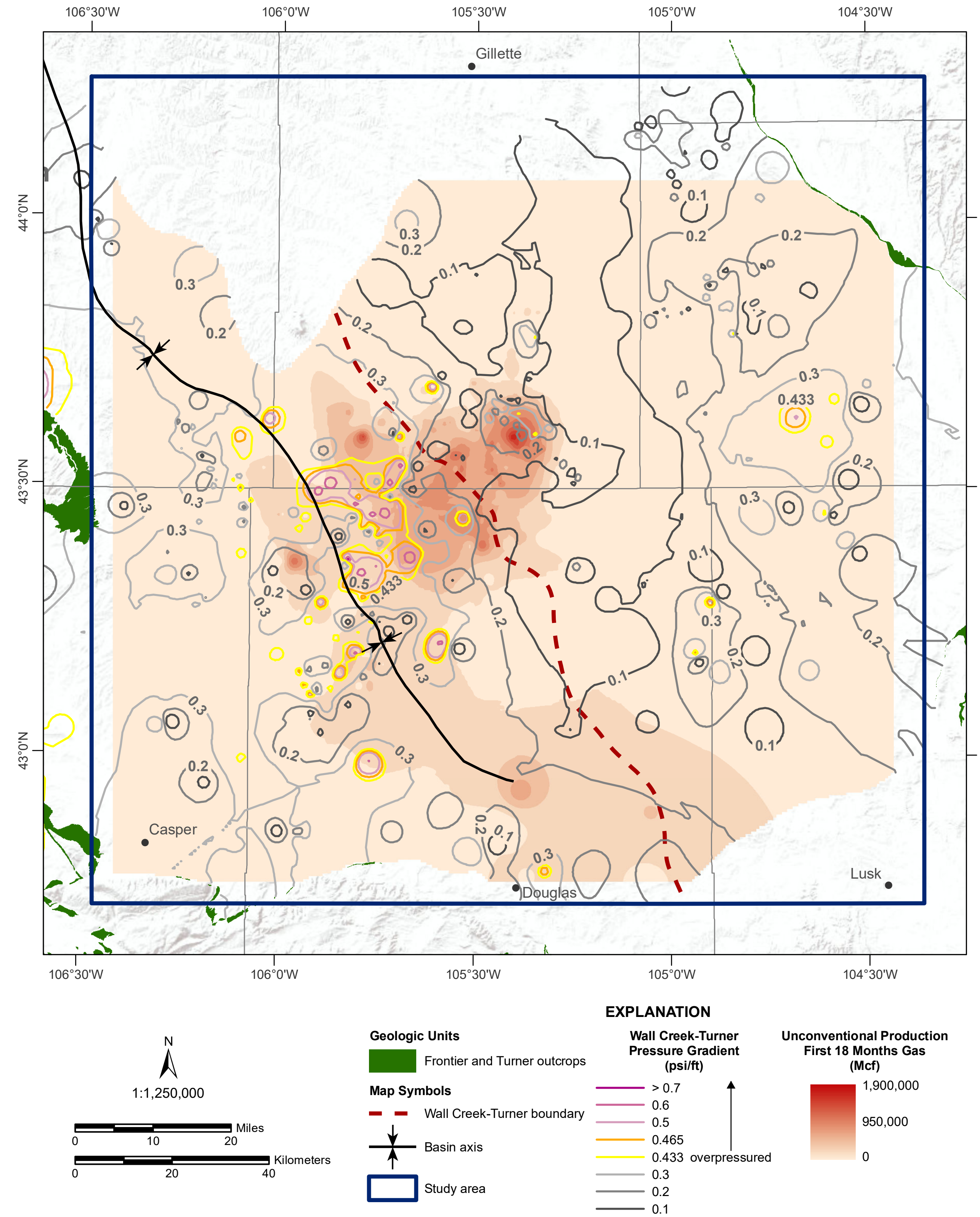

Figure 38. Pressure gradient contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

Temperature

Reservoir temperature can influence hydrocarbon viscosity and flow, associated reservoir pressure, and well production. This study therefore investigated the PRB Wall Creek and Turner reservoirs' thermal system by compiling temperatures recorded on well logs, initial production reports, and DST for 1,018 horizontal and vertical wells (IHS, 2018; WOGCC, 2018). Due to inherent issues in using well log temperatures to reflect true reservoir temperature, several quality control filters were applied to the raw temperature data. If reported on a well log, the temperature had to be from a log type that was not a cement bond or casing/collar log, as drying cement radiates heat and artificially elevates the recorded temperatures. In addition, because log temperatures are generally cooler compared to the true reservoir temperature (McPherson and Chapman, 1996), if multiple log temperatures were available for a single well, the maximum recorded temperature was included in the dataset. Finally, to get a standard, comparable formation temperature from the top of the Wall Creek or Turner reservoirs—instead of at varying levels within or even above or below the reservoirs—all temperatures were corrected using the following equation (modified from Asquith and Krygowski, 2004):

$$Tf = \left(\frac{(Tr - AMST)}{TD} * FD \right) + AMST$$

where Tf = formation temperature (at top of Wall Creek or Turner); Tr = temperature recorded during DST or on well log; AMST = annual mean surface temperature (spatially extracted from the 30-year annual mean temperature raster; Oregon State University, 2018); TD = vertical depth at which Tr was collected; FD = formation depth (top of Wall Creek or Turner from WSGS interpretations or WOGCC geologic markers).

The quality control filters and correction equation improve the consistency, accuracy, and approximation of the recorded temperatures to formation temperatures. However, without applying more robust corrections, such as those used by McPerson and Chapman (1996), Crowell and others (2012), and Aabø and Hermanrud (2019), these data should be considered an approximate analog to the actual reservoir temperature.

Interpolating and contouring the corrected formation temperatures indicates that temperatures at the top of the Wall Creek and Turner reservoirs range from less than 100°F near the margins of the PRB to greater than 225°F along the basin's axis (figs. 39 and 40). The highest top-of-reservoir temperature (321°F) is from an oil well in south-central Campbell County north of the high-unconventional gas area (API number 49-005-62049). Although the deepest portion of the basin consistently exhibits the highest reservoir temperatures, a noticeable lobe of high temperature also extends northeast into the shallower Turner reservoir.

When the temperature contour lines are draped over Wall Creek-Turner horizontal wells' first 18 months of production (figs. 39 and 40), the northeast-extending lobe of high temperature lies over the area of elevated gas production. It also aligns well with the areas of high GOR and API gravities, but is not within an overpressured portion of the reservoir. Patterson (2017) acknowledges similar "hot spots" in Chesapeake Energy leaseholds in Campbell and Converse counties. The positive correlation between temperature and Wall Creek-Turner oil and gas production is supported by the R values in table 8.

Table 8. Statistical correlation between Wall Creek-Turner unconventional oil and gas production surfaces and top-of-reservoir temperature surface.

Wall Creek-Turner product	R value (temperature)
unconventional first 18 months oil	0.55
unconventional first 18 months gas	0.43

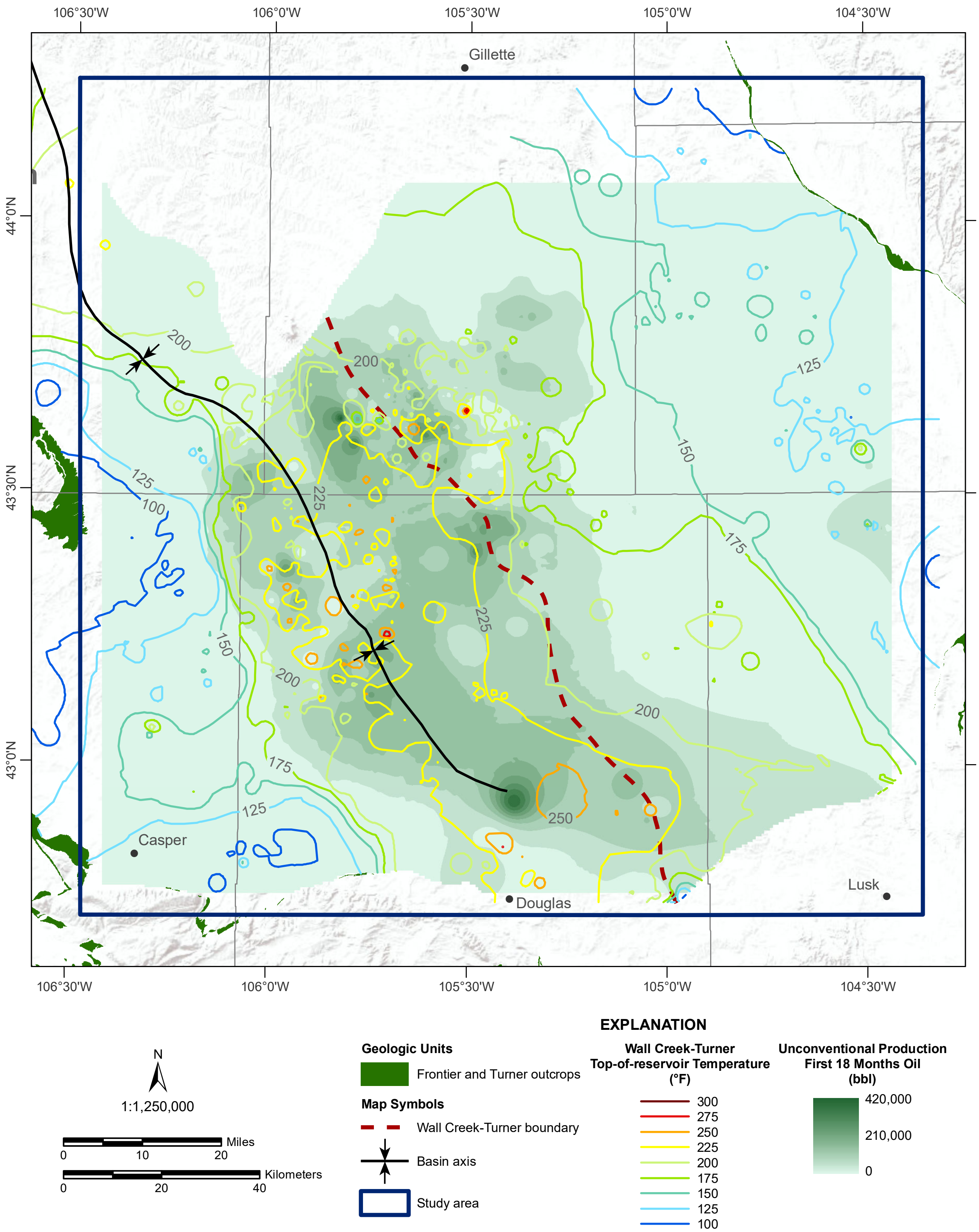

Figure 39. Top-of-reservoir temperature contours and first 18 months of unconventional oil production from the Wall Creek-Turner reservoir.

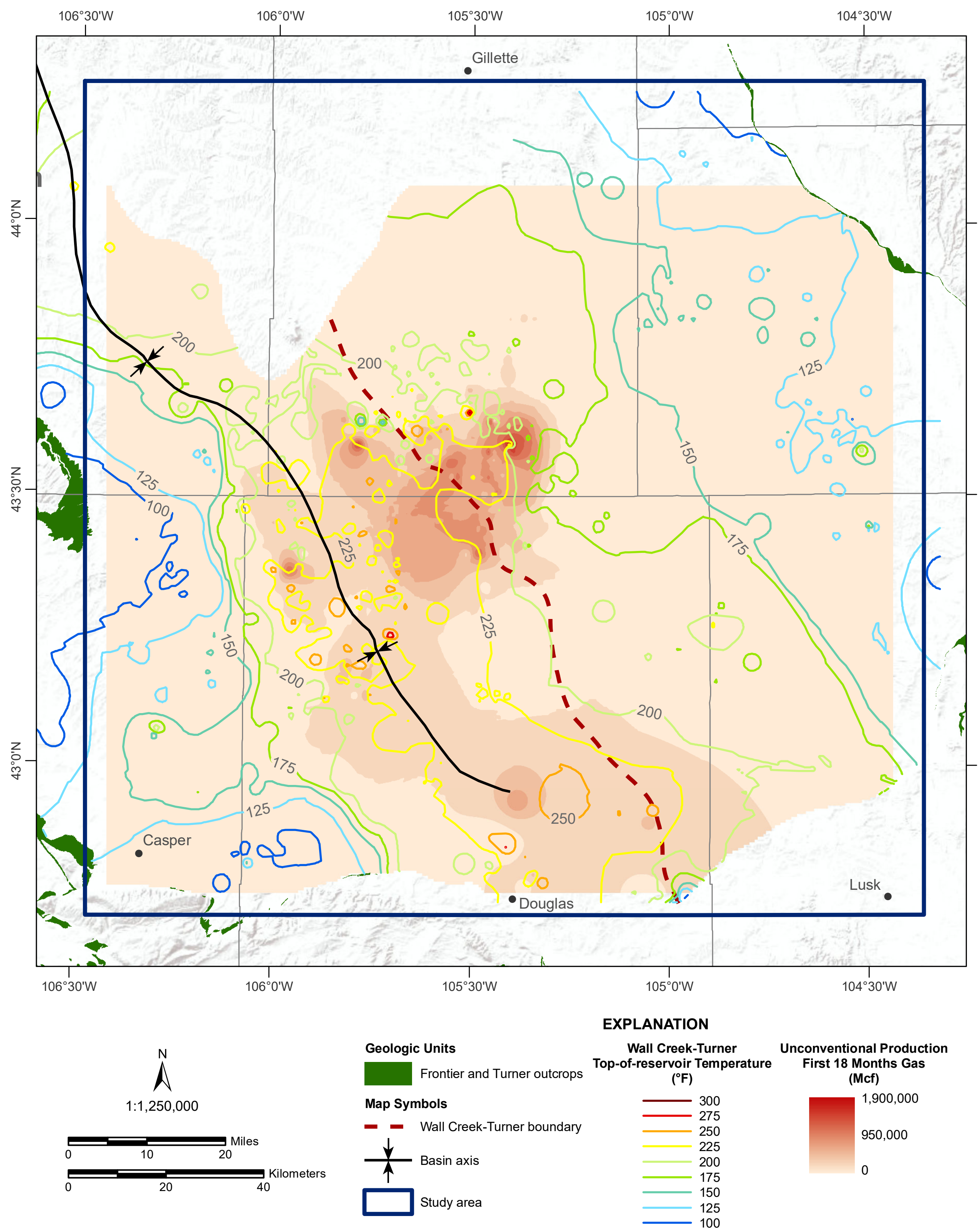

Figure 40. Top-of-reservoir temperature contours and first 18 months of unconventional gas production from the Wall Creek-Turner reservoir.

DISCUSSION AND SUMMARY

Understanding the factors that influence hydrocarbon production from the PRB Wall Creek and Turner reservoirs can drive and expand their development. This study's compilation and comparison of multiple datasets highlights what does and does not correlate with the most productive Wall Creek-Turner horizontal wells. Each possible influence on horizontal production is evaluated below.

Wall Creek Versus Turner

This study was not able to determine if the PRB Wall Creek and Turner sandstones should be considered one reservoir or evaluated separately. Both are capable of producing large quantities of oil and natural gas with similar hydrocarbon compositions. However, differences in their depositional environments and post-depositional history may have influenced their individual reservoir characteristics.

As a result of being deposited closer to its sediment source, regional Laramide uplifts, and the PRB axis, the Wall Creek has been subjected to more extreme deformation processes than the Turner. It is a deeper, hotter, and more overpressured reservoir (figs. 4, 37–40). It contains some of the thickest sand intervals found in the Wall Creek and Turner reservoirs, but does thin abruptly to the north (fig. 5). The Wall Creek has been the primary target and producer of conventionally produced oil and associated natural gas, and the areas with the most unconventionally developed oil can also be found within the Wall Creek reservoir.

The Turner, located east of the axis in more gently dipping strata, is found at shallower depths, and is cooler and less overpressured than the Wall Creek (figs. 4, 37–40). The Turner is also a more consistent thickness throughout the basin, although it does appear to thicken near the eastern basin margin (fig. 5). The overall consistency in the Turner is probably a result of its more distal deposition and less active tectonic history. While it was less targeted and had less conventional oil and gas production than the Wall Creek, the Turner reservoir has now become a primary focus of unconventional development in the PRB. Most of the basin's Turonian horizontal wells have been drilled in the Turner, with many proving to be good oil producers. Average cumulative Turner oil production (142,600 bbl/well) currently outpaces Wall Creek wells (138,800 bbl/well). The Turner has also shown to be the better natural gas producer of the two sandstones, mostly due to the gas-condensate sub-reservoir documented in this study.

Operator

In production cross-plots, several operators do stand out as having the highest-producing wells and maintaining high production throughout their wells' first years online, but still show a noticeable spread in the success of their wells (figs. 7–10). This production variation within operators holds true for both older and newer wells. It appears some operators have learned how to maximize initial production and extend it beyond typical decline curves (Appendix 2). However, when production is compared over a longer standard timescale (first 18 months), the operators' newest wells—completed with presumably the most effective techniques—are commonly matched or even outperformed by their older counterparts. Although well locations and changing sedimentary facies may partly account for some of the operator production differences, it does not explain the production variation in operators' wells drilled in close proximity to one other.

Lateral Producing Interval Length

It is generally assumed that the longer a horizontal well's lateral, the more reservoir surface it intersects, and the greater the probability of high production yields. Surprisingly, this assumption does not appear to hold for Wall Creek-Turner wells. Although most operators have chosen to complete wells with producing intervals shorter than 5,000 ft, especially in the Turner, even those operators who have extended their wells' producing lengths do not always see a corresponding increase in production (fig. 11). Higher average production from producing intervals longer than 8,000 ft may be biased by the limited number of wells with these lengths. The uncertain production benefits of a longer lateral in the Wall Creek-Turner reservoir may not be worth the increased drilling cost.

Lateral Orientation

Operators have drilled mostly N–S-oriented laterals in the PRB Wall Creek and Turner reservoirs. Horizontal well laterals are typically oriented perpendicular to S_{Hmax} in order to maximize induced fractures and capitalize on intersecting natural fractures. However, the Wall Creek-Turner lateral orientations appear to be a result of predetermined "stand-up" drilling spacing units, as neither N–S nor E–W wells are optimally oriented to the PRB's present-day S_{Hmax}. These non-optimal orientations are reflected in the weak influence that current lateral azimuths have on Wall Creek and Turner horizontal well production. Although N–S wells have the highest average production, they also exhibit large variability in their first 18 months of production—even within the same operator, and wells drilled E–W can individually perform just as well as N–S wells (figs. 12 and 13). This is supported by comparisons of spatially proximate well groups—owned by the same operator and with similar producing interval lengths—where the E–W well outperforms its N–S neighbor. The variability in lateral orientations and associated production may be due to preservation of complex stress regimes or undocumented sedimentological trends within the Wall Creek and Turner reservoirs. As the PRB Wall Creek-Turner play continues to be developed, more variation in lateral azimuth may refine the influence of orientation on production.

Completion Techniques

This study's evaluation of frac stages, slurry volume, and proppant volume documents that operators in the Powder River Basin generally complete wells in the Wall Creek and Turner reservoirs using an operator-specific standard formula. These standard methods yield a range of first months' production success, and even those operators who do vary their formula do not see increased production returns using larger completion jobs (figs. 14–16). As such, there is not yet an established optimum range of hydraulic fracturing parameters for wells completed in the PRB's Wall Creek and Turner reservoirs.

Reservoir Depth and Thickness

The most prolific Wall Creek-Turner oil wells—both vertical and horizontal—are located in the Wall Creek reservoir near the deepest part of the basin, but in thinner sections of the reservoir (figs. 17, 18, 20, and 21). Natural gas production from vertical Wall Creek-Turner wells follows the same deep, basin-axis-parallel spatial trend as an associated by-product of conventional oil production (figs. 23 and 25).

Horizontal Wall Creek-Turner oil wells, however, do not produce the same large quantities of associated natural gas as vertical wells. Instead, primary unconventional natural gas production from the Wall Creek and Turner is concentrated in the shallower areas of the Turner reservoir between areas of high unconventional oil production (fig. 22). This area of elevated gas production is located in or near some of the thinner sections of the reservoir (fig. 24).

Statistical correlations document a strong positive correlation between Wall Creek-Turner oil and gas production and depth, while thickness is weakly correlative at best. Production from the Wall Creek-Turner appears to be more dependent on targeting hydrocarbon-rich zones within the reservoir interval rather than the overall reservoir thickness itself.

Gas-Oil Ratio

The highest gas-oil ratios in the PRB Wall Creek and Turner spatially bound areas of elevated gas production, while generally skirting the highest oil production areas (figs. 26 and 27). Statistical correlations confirm a weak-to-absent correlation between GOR and oil production but a moderate positive correlation with gas production. The interpolated GOR contours may indicate where high gas production may be encountered in as-yet undeveloped areas.

API Gravity

Initial crude oil API gravities exhibit a strong positive correlation, both spatially and statistically, with the most productive wells (figs. 28 and 29). Southern Campbell County wells with oil API gravities greater than 45° tap into a different type of Turner reservoir—gas-condensate. Undeveloped portions of the Wall Creek and Turner reservoirs with similarly high API gravities may contain additional gas-condensate sub-reservoirs. The 45°–50° API gravity contours also encompass most areas of high unconventional oil production, suggesting that hydrocarbons from these reservoirs are light and marketable.

Natural Gas Composition

While this study attempted to evaluate reservoir thermal maturity and possible migration pathways using natural gas compositions, the limited number of publicly available analyses precludes identifying definite patterns or correlations within the Wall Creek and Turner reservoirs (figs. 30 and 31).

Tectonics

Regional lineaments transecting the study area may have influenced the location of Upper Cretaceous reservoirs' most productive areas. This study shows that the areas of highest Wall Creek and Turner conventional and unconventional production spatially align with and are bordered by these lineaments (figs 32 and 33).

Pressure

Areas with the most PRB Wall Creek and Turner oil and gas production have little-to-no spatial overlap with the overpressured portions of the reservoirs (figs 37 and 38). This is partly because the most overpressured areas of the Wall Creek have not yet been targeted by unconventional development. R values that document a statistically moderate negative correlation of production with reservoir pressure gradients may change as operators start completing horizontal wells in the higher-pressured portions of the reservoir. It is worth noting that operators are able to produce large oil and gas volumes from the Wall Creek and Turner under normally pressured and underpressured reservoir conditions. The discontinuity in overpressure throughout the Wall Creek and Turner also implies that distinct pressure compartments may exist within these reservoirs, further complicating hydrocarbon exploration and development.

Temperature

Temperature is the one reservoir attribute with a strong spatial correlation to Wall Creek-Turner production, especially in regard to natural gas production. This spatial correlation is supported by moderately positive statistical correlations between both oil and gas production and reservoir temperature. Almost all areas of high unconventional oil and gas production occur at reservoir temperatures greater than approximately 200°F (figs. 39 and 40). Reservoir temperatures greater than 225°F outline and establish an area of higher heat flow corresponding to the gas-condensate region in southern Campbell County. This spatial relationship suggests that temperature analyses could be used to identify other potential gas-condensate sub-reservoirs within the Wall Creek and Turner.

POTENTIAL FUTURE WORK

Although this study attempts to supplement the current understanding of the Wall Creek and Turner reservoirs, it also highlights issues requiring further analysis. The following are potential ideas for extending this investigation's findings.

This study encountered extensive Frontier Formation nomenclature variation in public databases. Due to limited time and resources, the exact sand interval reported by the databases was unable to be determined when generic formation terms such as "Frontier" were used. A broad assumption was made that operators were probably targeting the best-producing sand—the uppermost Wall Creek Sandstone—increasing the potential for including non-Wall Creek Sandstone data. A more detailed study of which Frontier sand interval was reported would eliminate some of the error introduced to the dataset.

The lack of strong correlation between PRB Wall Creek and Turner horizontal well producing interval length and increased production shown in this study is perplexing. The longer the interval, the more reservoir surface area it intersects, and theoretically, the higher the production. It is possible that the longer laterals are encountering a larger number of less productive sedimentary facies. Longer horizontal Wall Creek-Turner wells may also take more than 18 months to start outperforming their shorter counterparts, and operators may still be learning how to optimize their lateral lengths in these sandstones. Detailed facies analyses of the Wall Creek and Turner and extended evaluations of horizontal wells drilled in these reservoirs may help explain and refine whether producing interval length does influence production trends.

The number of publicly available gas composition analyses was not sufficient to definitively identify gas migration pathways within the Wall Creek-Turner reservoir or to characterize the thermal maturity of its hydrocarbons. Proprietary gas composition data from operators would extend the public dataset and help determine if such maturity or migration trends exist.

Most Wall Creek horizontal wells have been completed outside of the overpressured areas of the reservoir, yet many of these horizontal wells still yield good oil production. As operators expand their unconventional development into the overpressured Wall Creek (fig. 41), continued monitoring in these areas will contribute to understanding the association of reservoir pressure with production.

Although Wall Creek-Turner oil and gas production seems to spatially align with and be contained within paleotectonic lineament trends, a more detailed investigation is required to determine whether the association between these regional features and localized production is circumstantial or causal. One area where such a study would be especially useful is the gas-condensate area of the Turner reservoir. It is possible that localized structural features related to the broad regional lineaments or even a deep intrusive body could explain the higher heat-flow pattern and spatial compartmentalization of the gas-condensate area.

Finally, detrital zircon analyses of the Wall Creek and Turner may refine their depositional history and provenance. Sterling and others (2016) propose that the similarly-aged Turonian Codell Sandstone had an eastern source. The Turner also appears to thicken along the eastern PRB margin. A detrital zircon study may clarify whether the Turner is actually a down-dip facies extension of the Wall Creek or whether it had sediment input from a different source.

INTERACTIVE ONLINE MAP

This investigation's raster surfaces, associated contour lines, and wells used to create the surfaces were added to a supplementary geodatabase and interactive online map (available at the WSGS publications webpage; https://www.wsgs.wyo.gov/pubs-maps/publication-search). This online map allows users to customize their visual experience using interactive tools provided in the map. Users can restrict the map scale to a defined area of interest, choose which layers they wish to view simultaneously, superimpose layers on each other, and query the datasets for more detailed layer attributes. The online map functionality can facilitate spatial visualization of geologic attributes and which of those attributes influence production from the Wall Creek-Turner reservoir.

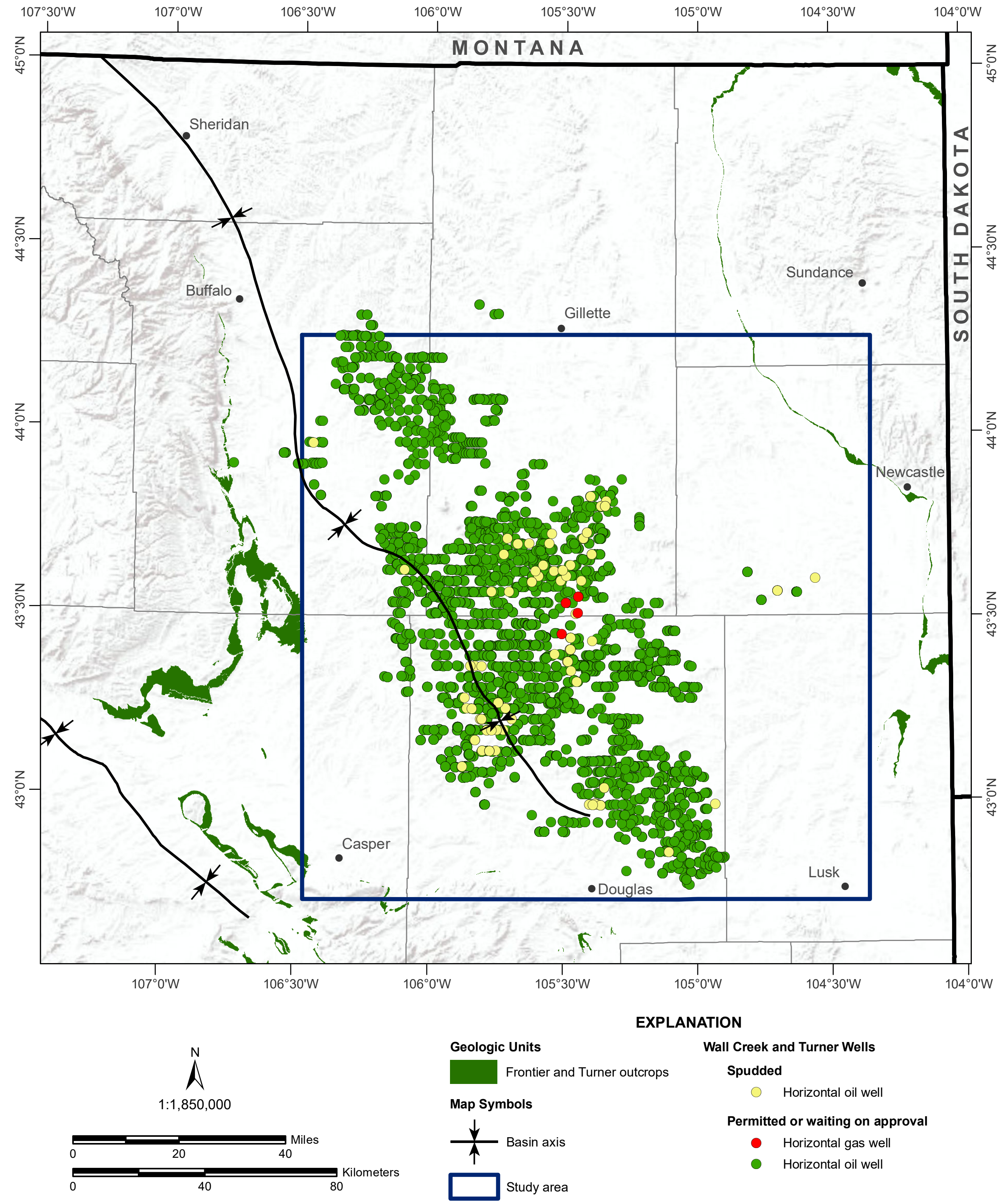

Figure 41. Possible future Wall Creek and Turner well locations. As of the WOGCC's December 31, 2018, download, these wells have a permit-to-drill, waiting-on-approval, or spudded status, and will target either the Wall Creek (permitted as Frontier) or Turner reservoirs.

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Appendices

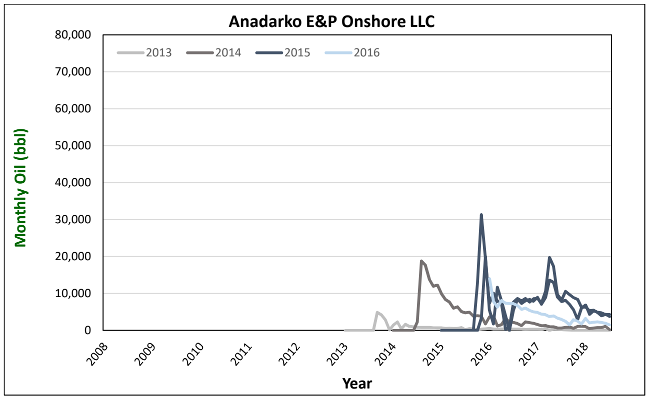
Appendix 1: Wall Creek-Turner well data

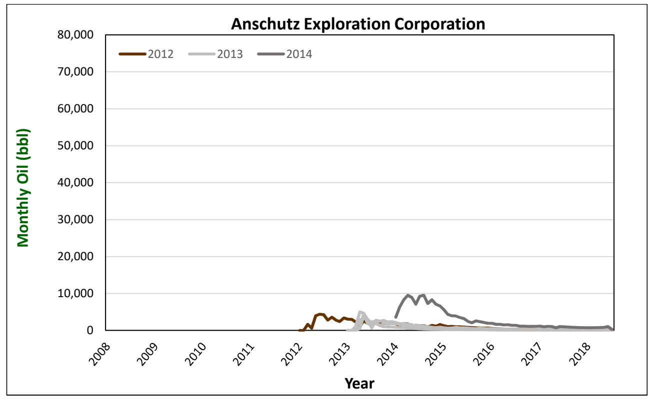
Appendix 1 is a spreadsheet of point data used in this investigation. Horizontal well completions, unconventional and conventional production, API gravities, gas-oil ratios, gas compositions, and temperature information is reported in individual tabs within the spreadsheet. Gas-oil ratios and raw drill stem test temperature and shut-in pressure values originating from IHS proprietary database cannot be publicly reported and are omitted from the spreadsheet.

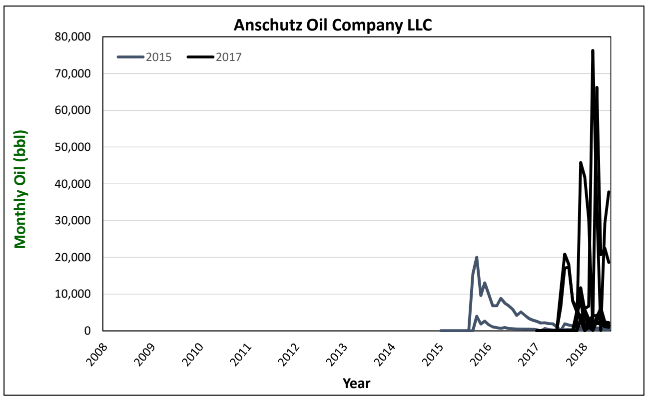
Appendix 1 is available as part of this investigation's zipped document on the WSGS publications webpage (https://www.wsgs.wyo.gov/pubs-maps/publication-search).

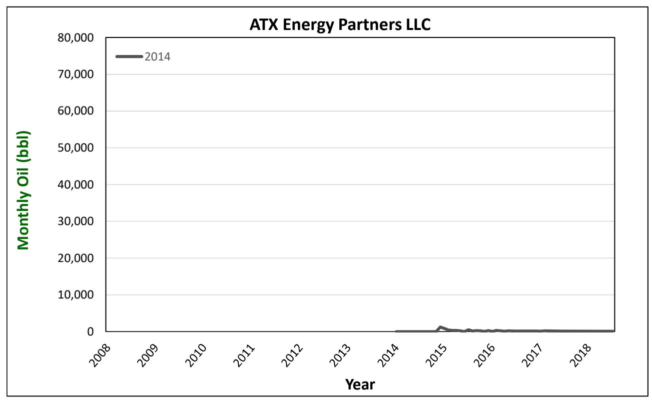
Appendix 2: Unconventional Wall Creek-Turner production through time

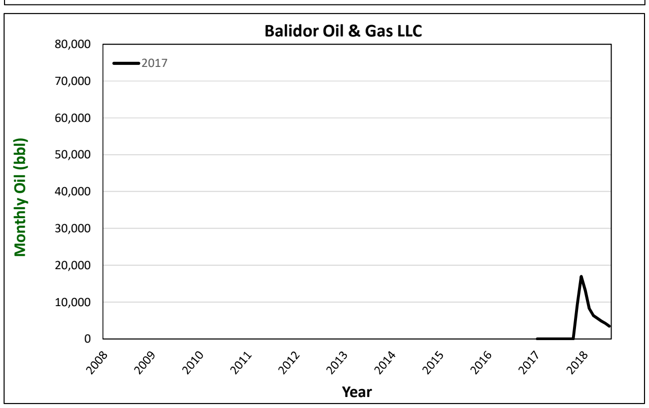
Part 1. The following charts display monthly oil production per operator throughout the life of each well. Production is shown from January 2008 through July 2018, although the earliest horizontal Wall Creek-Turner well came online in 1994 (Chesapeake API number 49-009-22804).

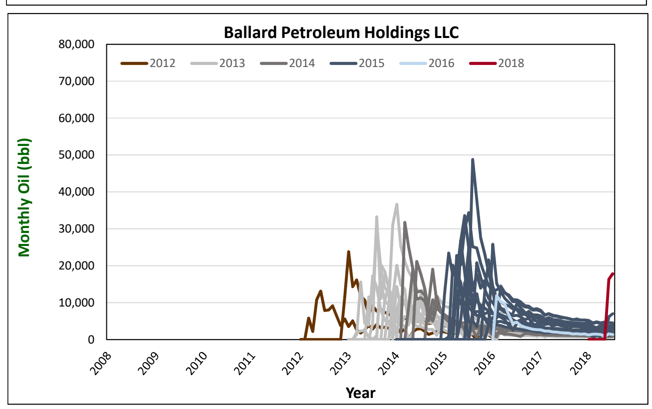


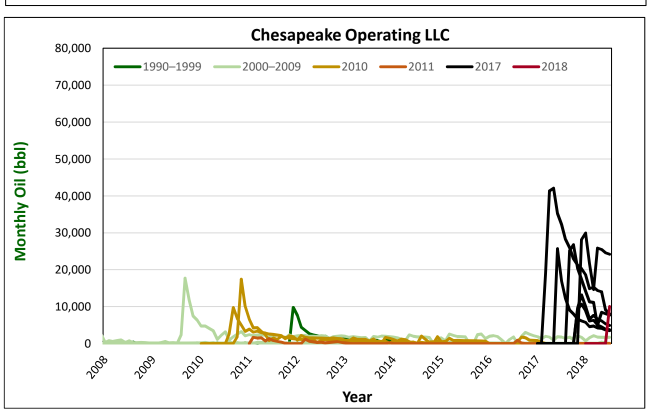


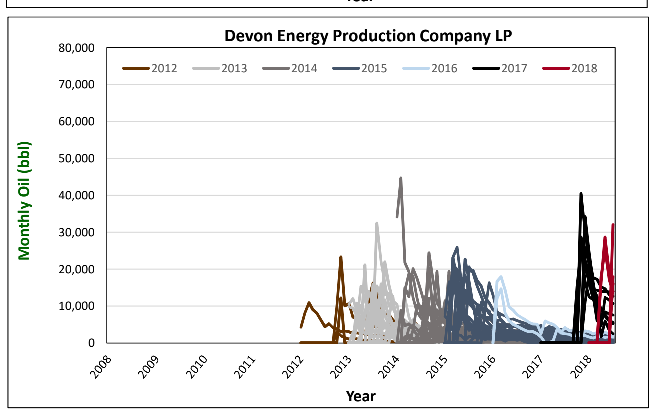


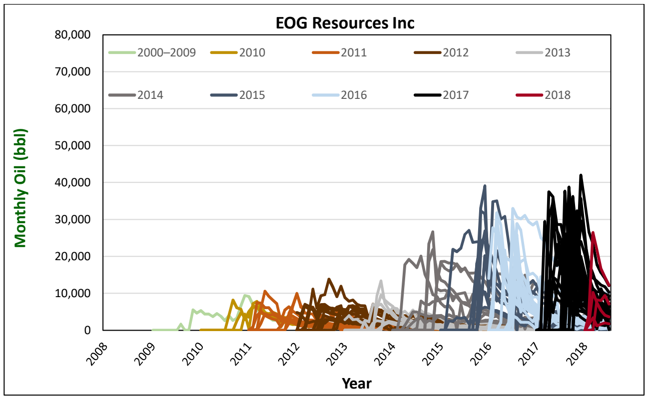


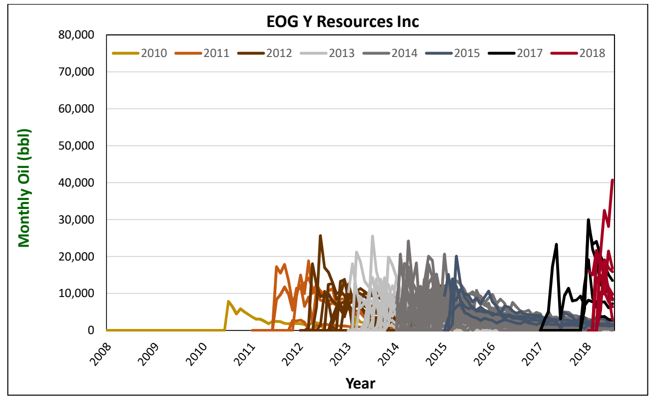


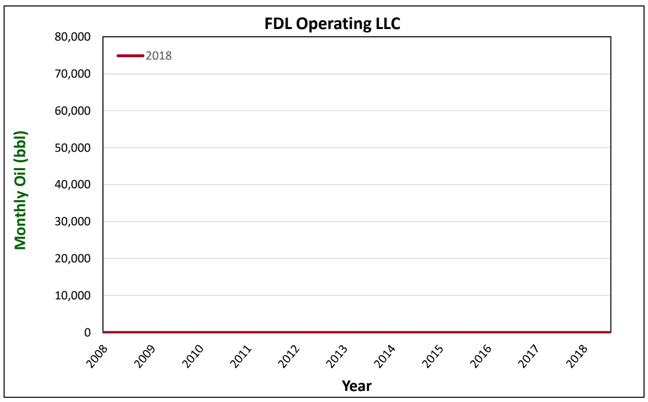


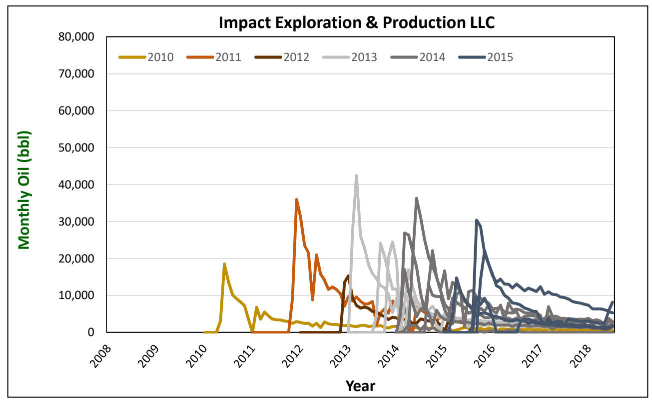


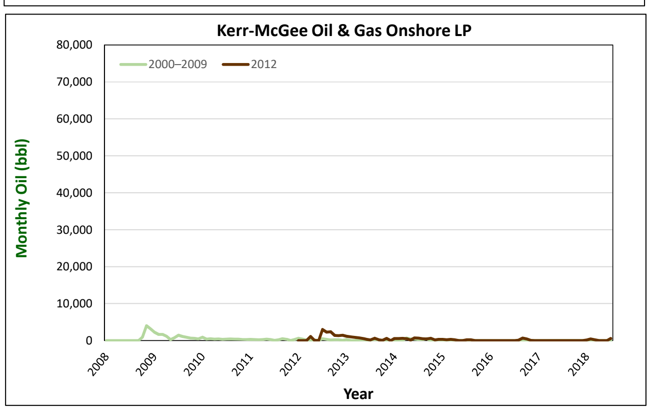


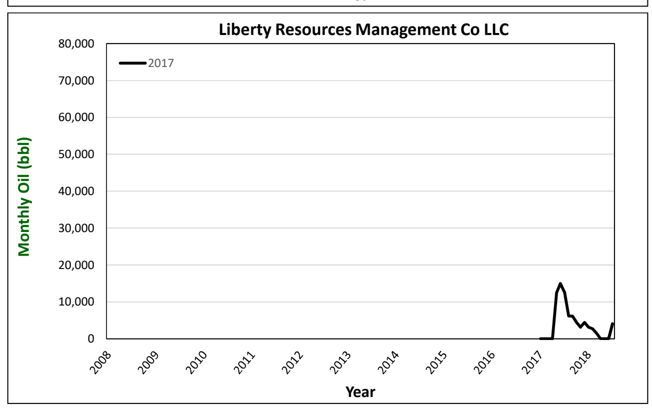

EOG Resources Inc
2000–2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

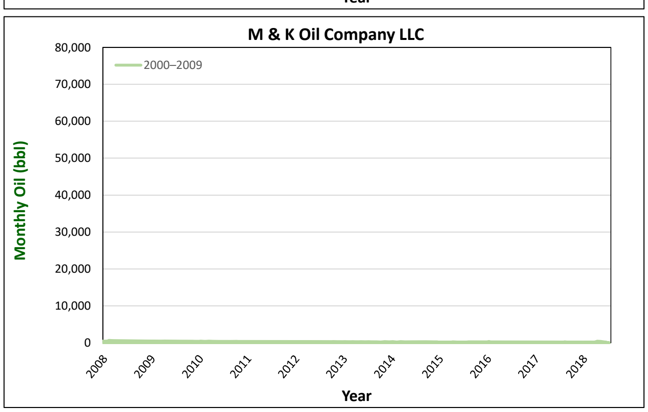

EOG Y Resources Inc
2010
2011
2012
2013
2014
2015
2017
2018
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

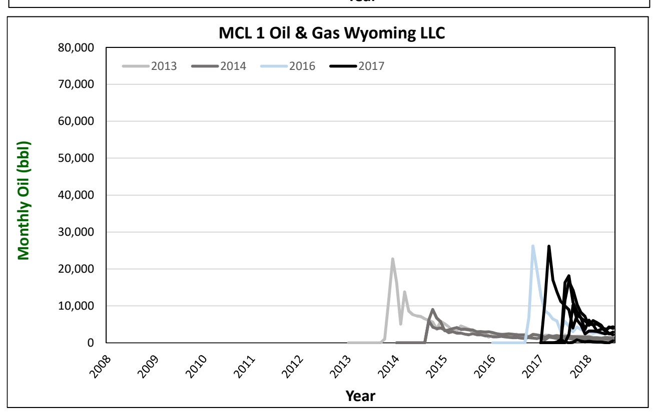

FDL Operating LLC
2018
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

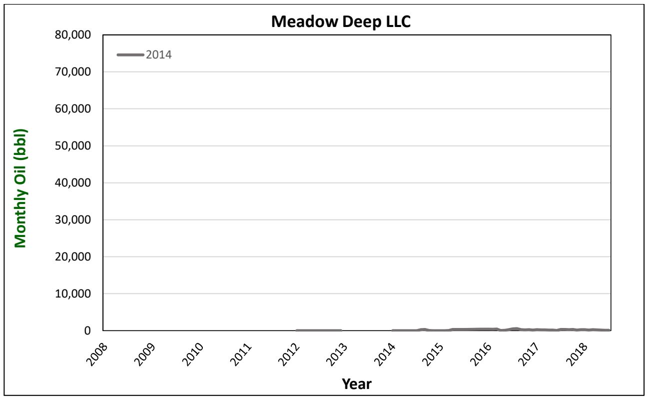

Impact Exploration & Production LLC
2010
2011
2012
2013
2014
2015
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

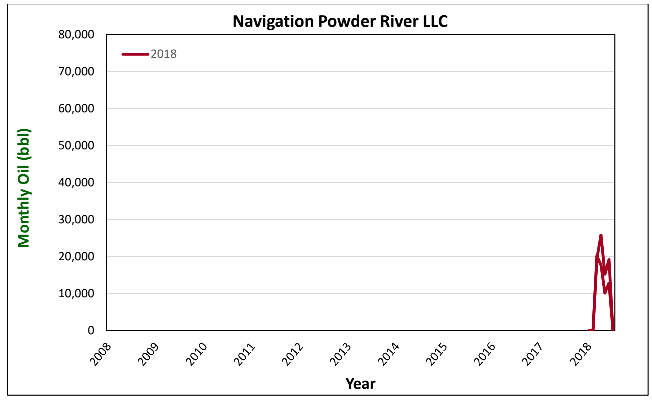

Kerr-McGee Oil & Gas Onshore LP
2000–2009
2012
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

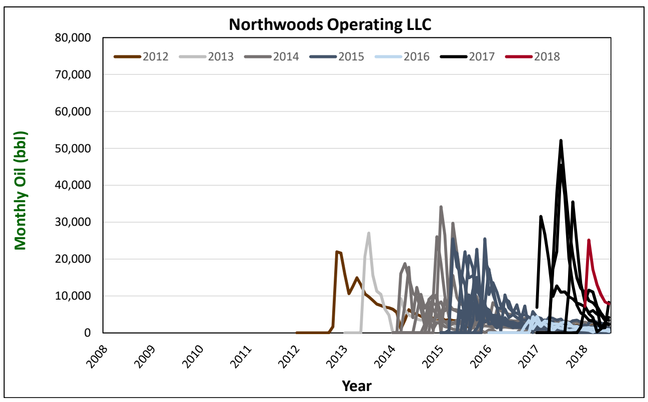

Liberty Resources Management Co LLC
2017
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

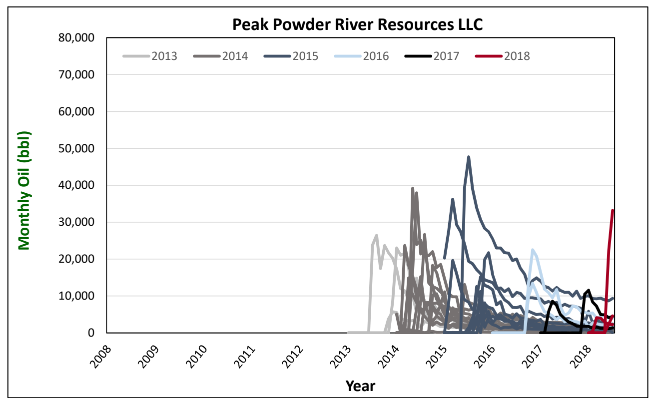

M & K Oil Company LLC
2000–2009
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

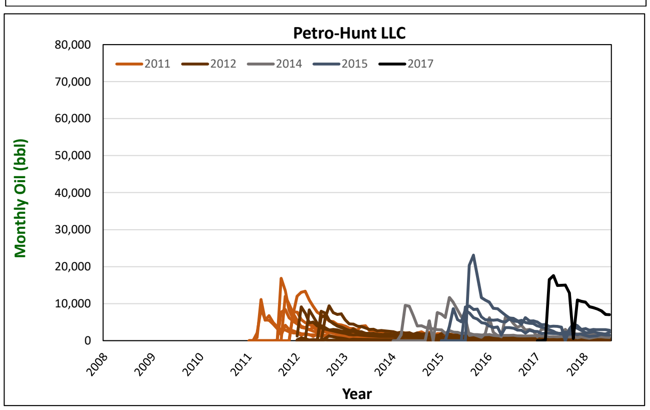

MCL 1 Oil & Gas Wyoming LLC
2013
2014
2016
2017
Monthly Oil (bbl)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year

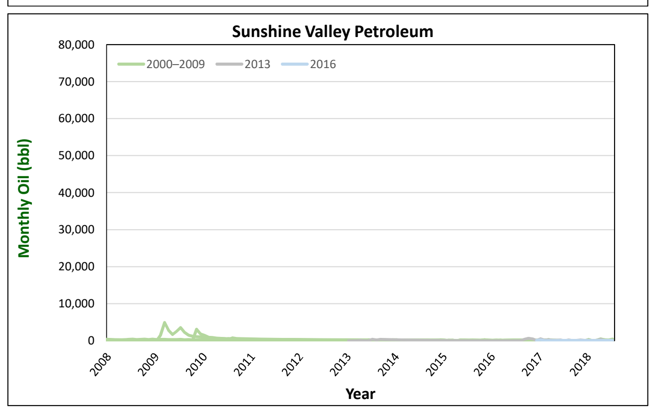

Meadow Deep LLC
2014
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

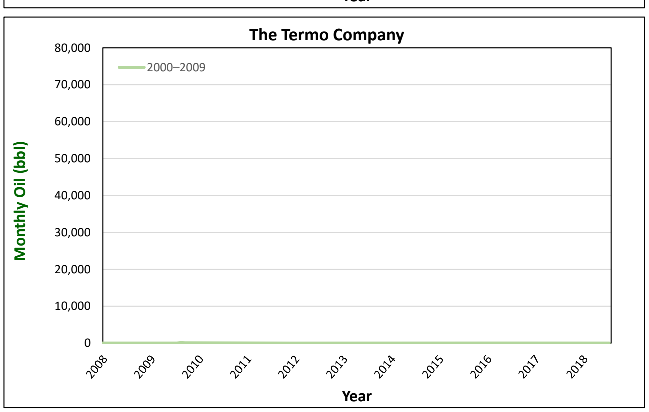

Navigation Powder River LLC
2018
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

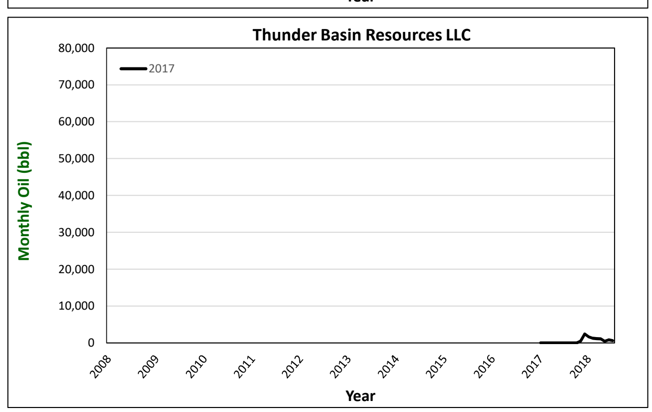

Northwoods Operating LLC
2012
2013
2014
2015
2016
2017
2018
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

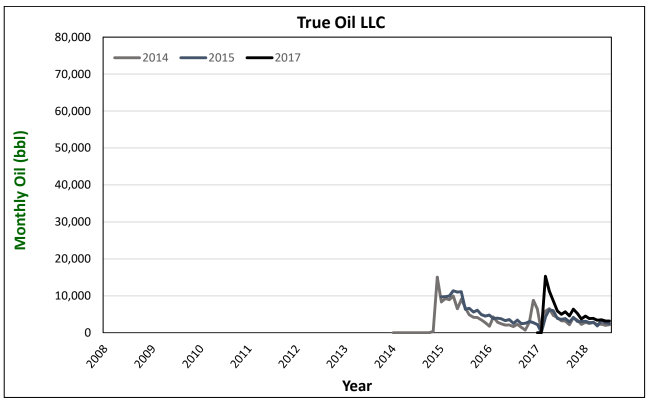

Peak Powder River Resources LLC
2013
2014
2015
2016
2017
2018
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

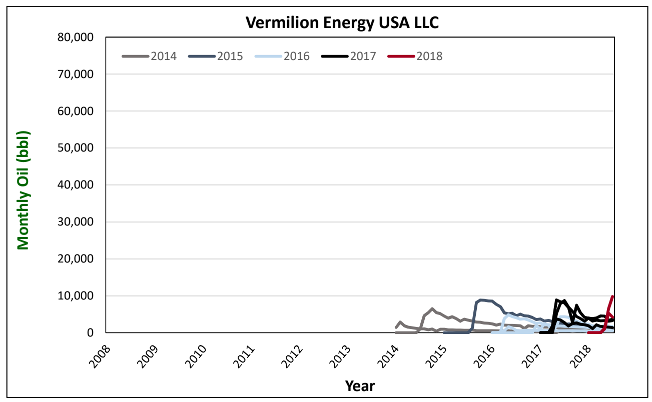

Petro-Hunt LLC
2011
2012
2014
2015
2017
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


Sunshine Valley Petroleum
2000–2009
2013
2016
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


The Termo Company
2000–2009
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


Thunder Basin Resources LLC
2017
Monthly Oil (bbl)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


True Oil LLC
Monthly Oil (bbl)
Year
2014
2015
2017
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018


Vermilion Energy USA LLC
Monthly Oil (bbl)
Year
2014
2015
2016
2017
2018
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
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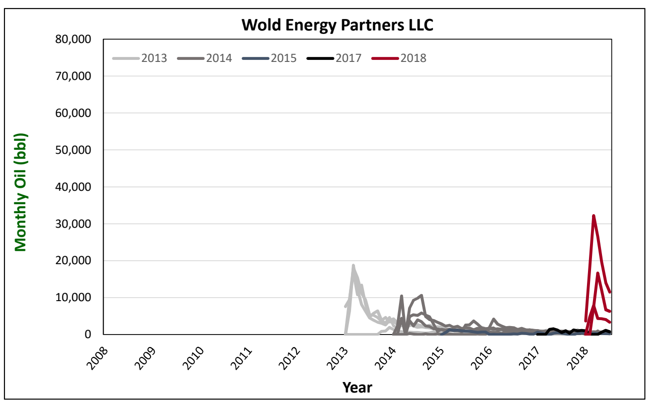
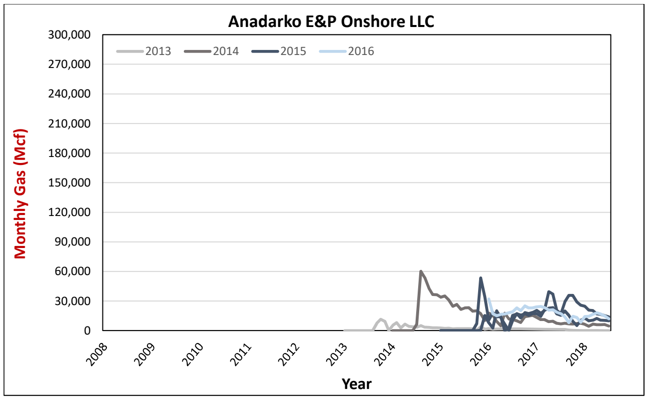
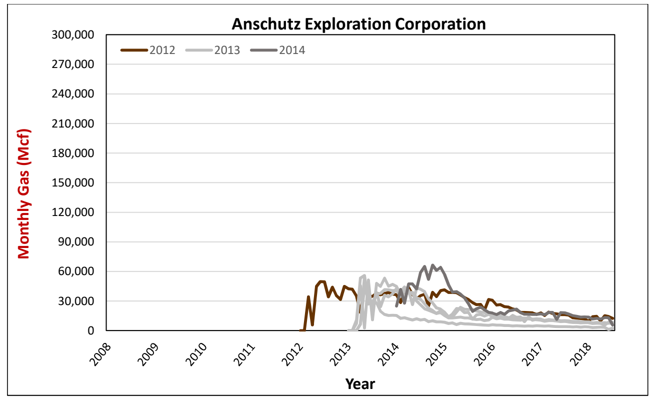
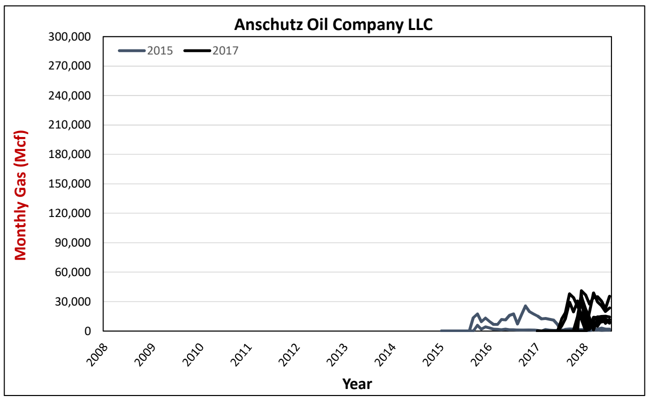
2013
2014
2015
2016
2017
2018

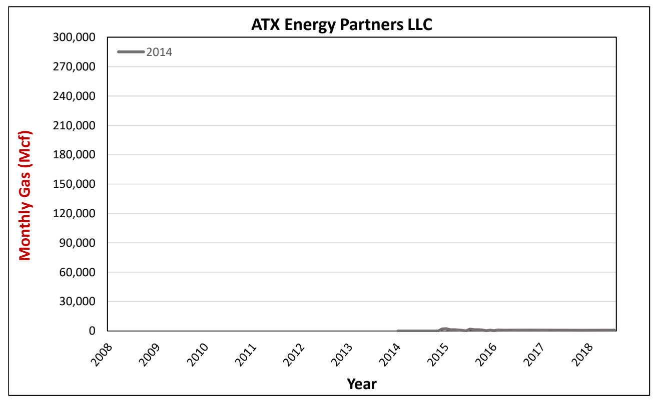

Wold Energy Partners LLC
Monthly Oil (bbl)
Year
2013
2014
2015
2017
2018
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

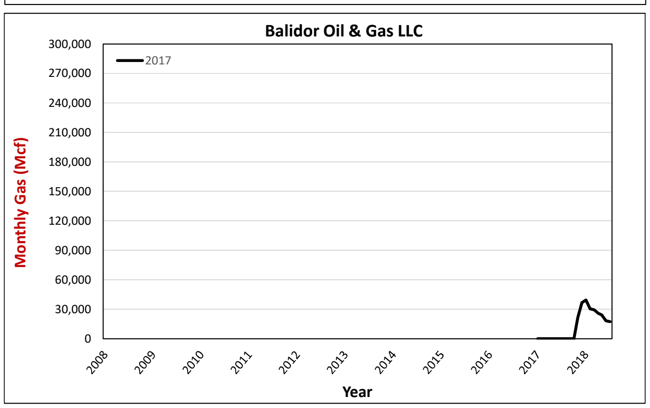
Part 2. The following charts display monthly natural gas production per operator throughout the life of each well. Production is shown from January 2008 through July 2018, although the earliest horizontal Wall Creek-Turner well came online in 1994 (Chesapeake API number 49-009-22804).

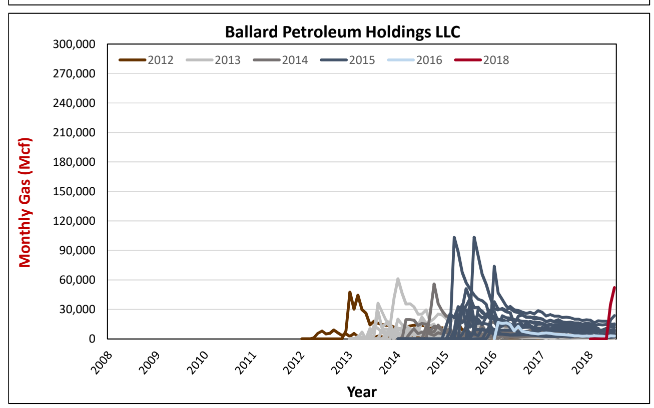


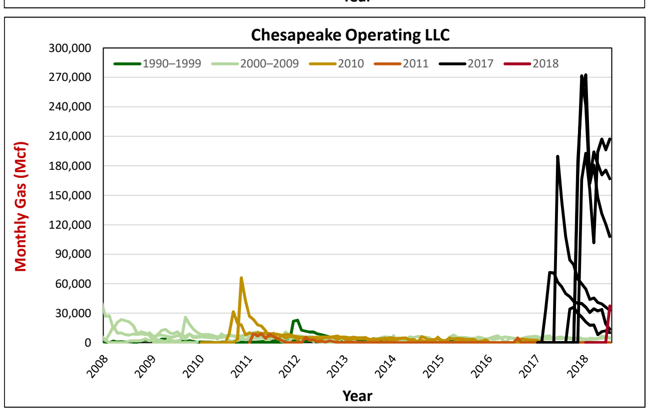


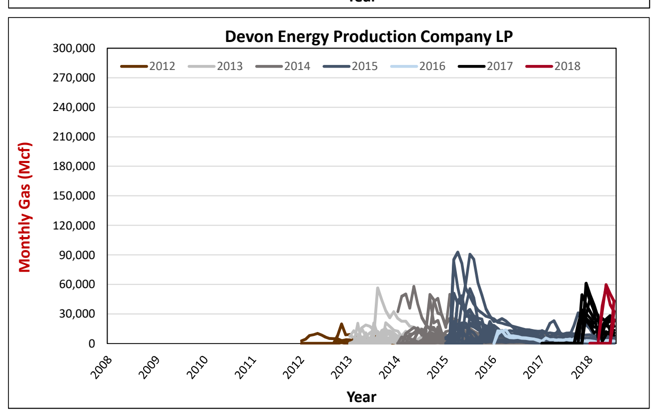


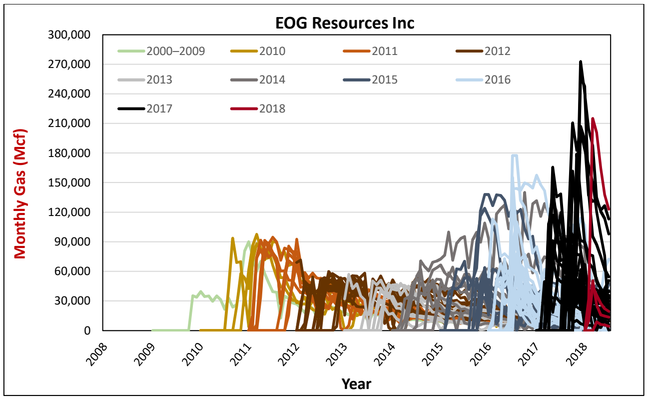


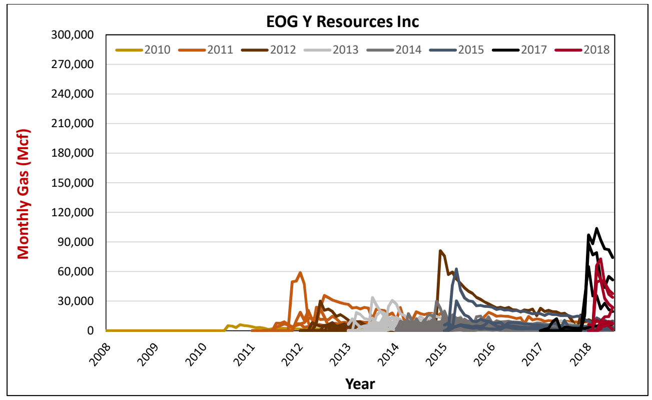









EOG Resources Inc
2000–2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


EOG Y Resources Inc
2010
2011
2012
2013
2014
2015
2017
2018
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
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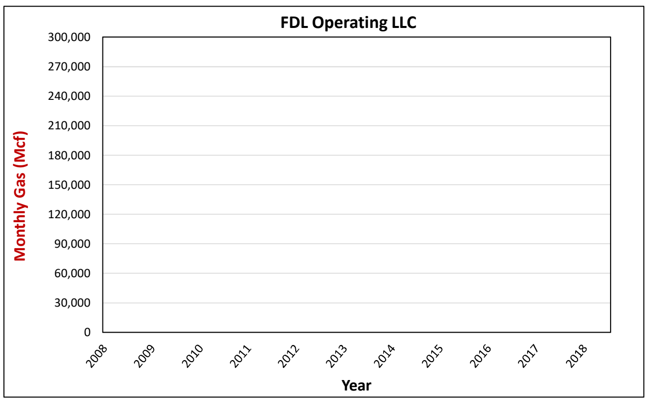
2016
2017
2018
Year


FDL Operating LLC
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
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2012
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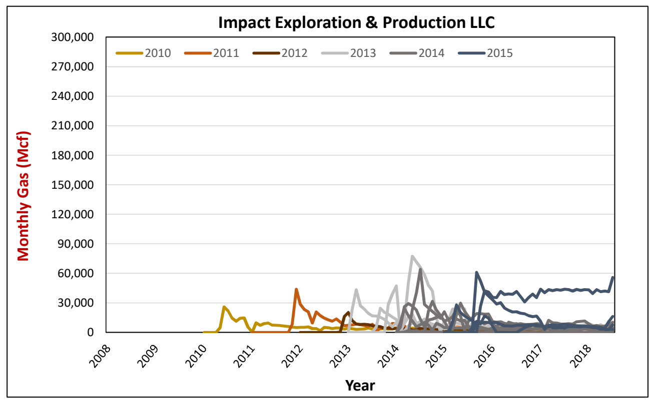
2016
2017
2018
Year


Impact Exploration & Production LLC
2010
2011
2012
2013
2014
2015
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
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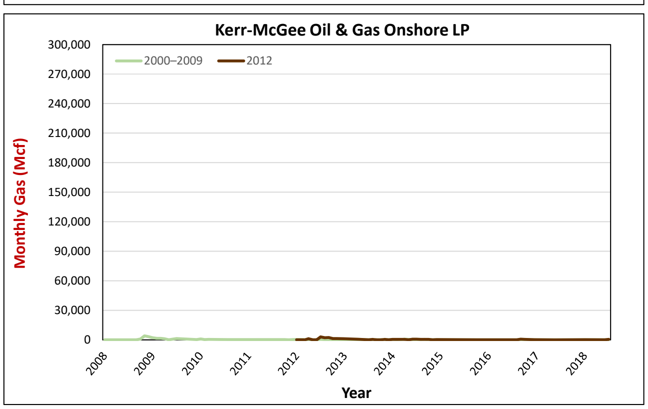
2016
2017
2018
Year


Kerr-McGee Oil & Gas Onshore LP
2000–2009
2012
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
2012
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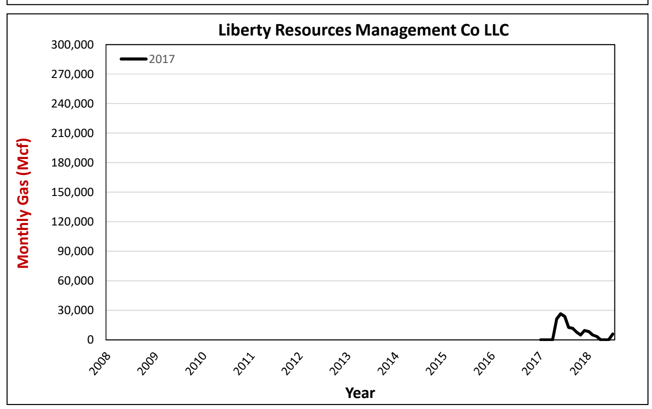
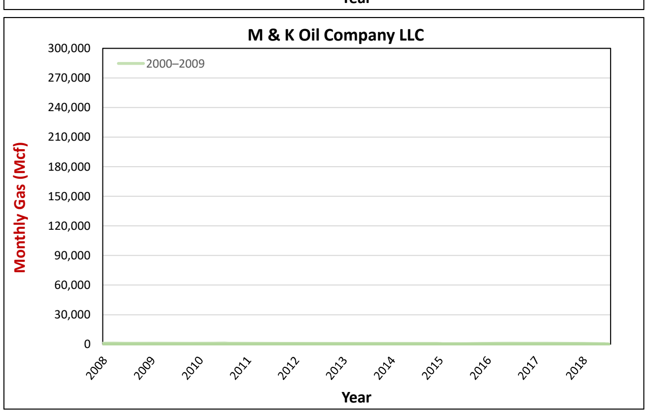
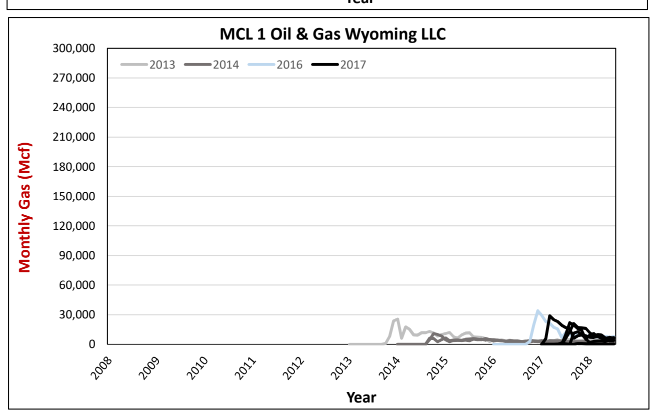
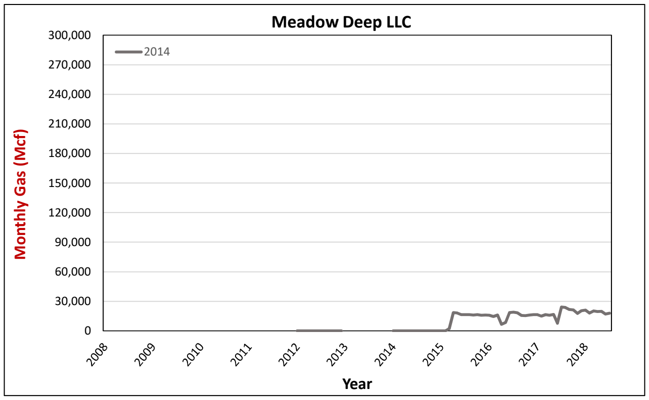
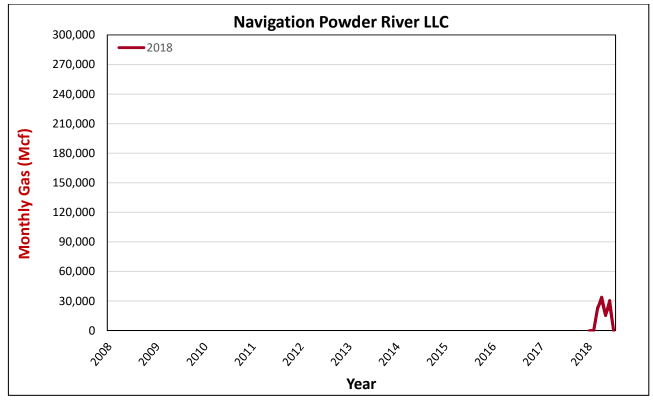
2016
2017
2018
Year

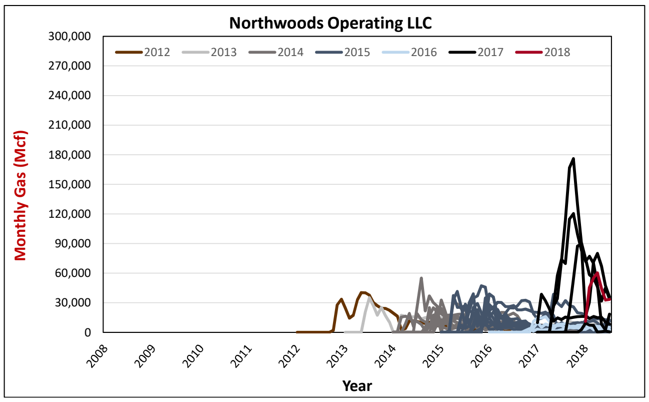

Liberty Resources Management Co LLC
2017
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

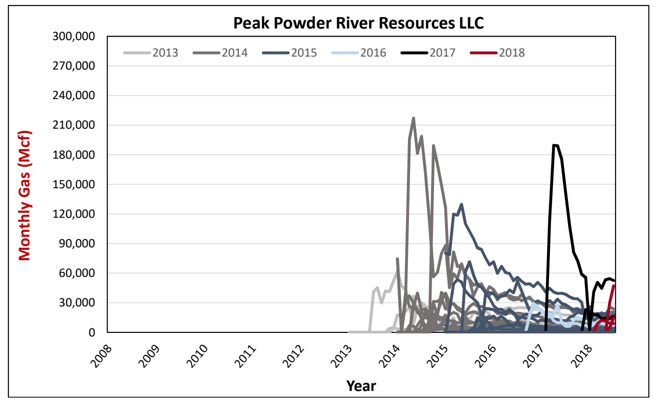

M & K Oil Company LLC
2000–2009
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

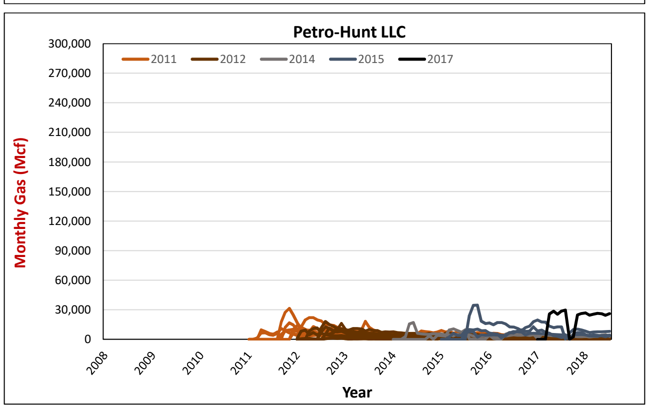

MCL 1 Oil & Gas Wyoming LLC
2013
2014
2016
2017
Monthly Gas (Mcf)
0
30,000
60,000
90,000
120,000
150,000
180,000
210,000
240,000
270,000
300,000
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

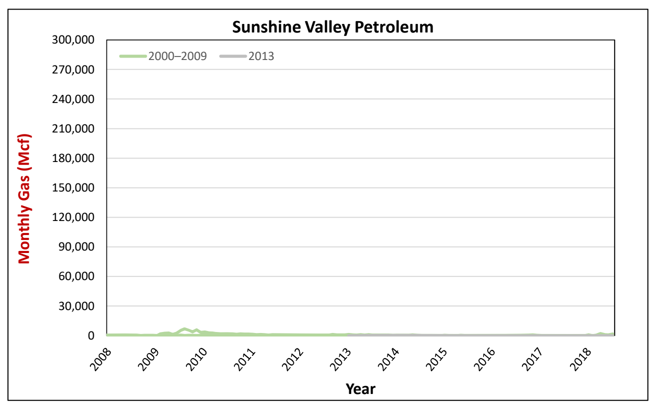

Meadow Deep LLC
2014
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

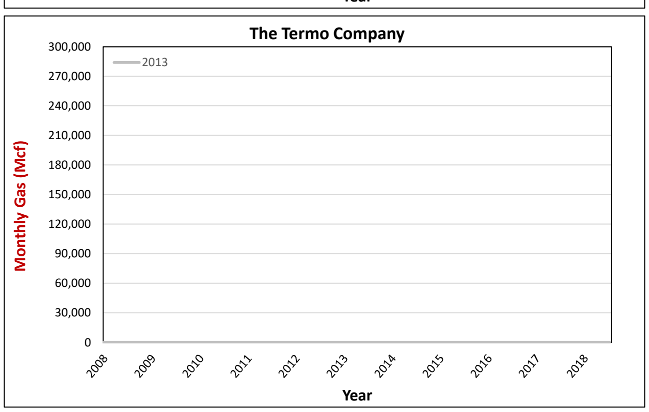

Navigation Powder River LLC
2018
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

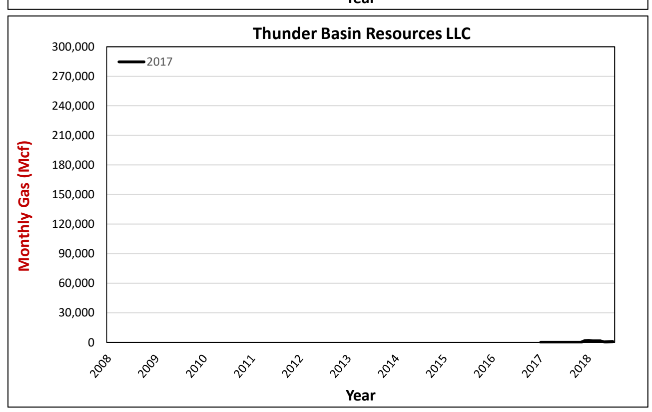

Northwoods Operating LLC
2012
2013
2014
2015
2016
2017
2018
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

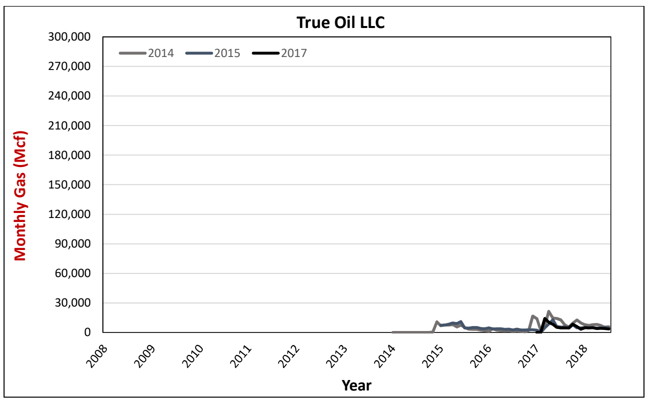

Peak Powder River Resources LLC
2013
2014
2015
2016
2017
2018
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

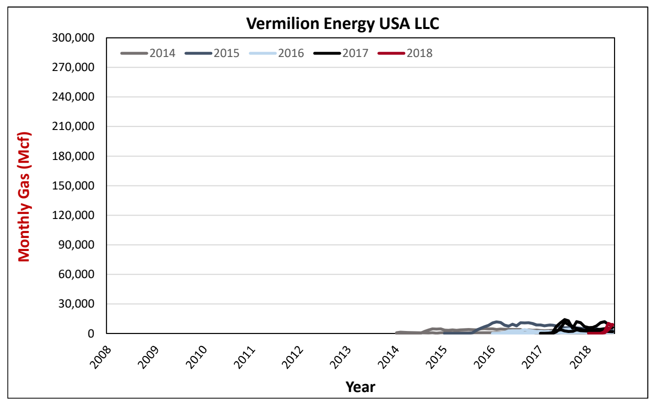

Petro-Hunt LLC
2011
2012
2014
2015
2017
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

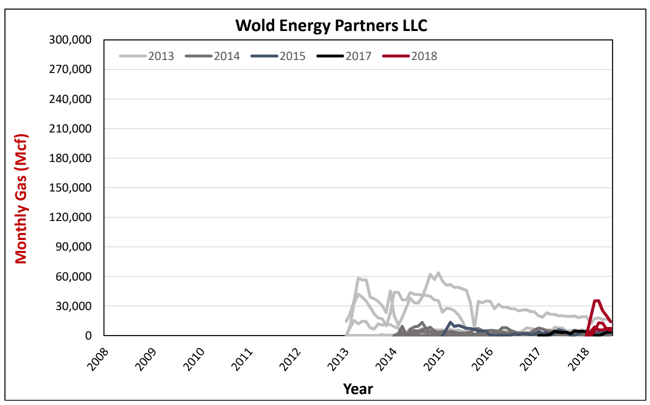

Sunshine Valley Petroleum
2000–2009
2013
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


The Termo Company
2013
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


Thunder Basin Resources LLC
2017
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

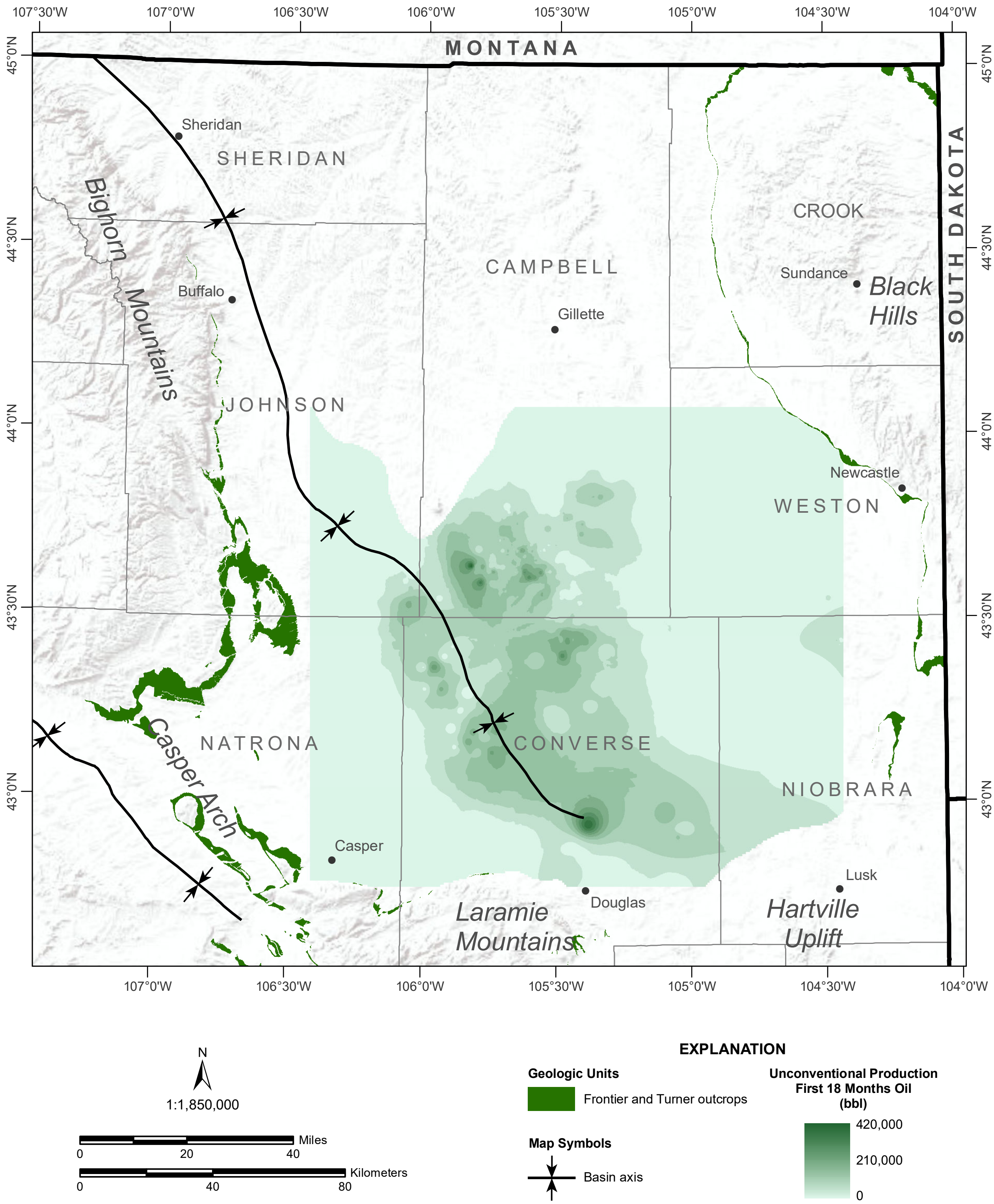

True Oil LLC
2014
2015
2017
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


Vermilion Energy USA LLC
2014
2015
2016
2017
2018
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

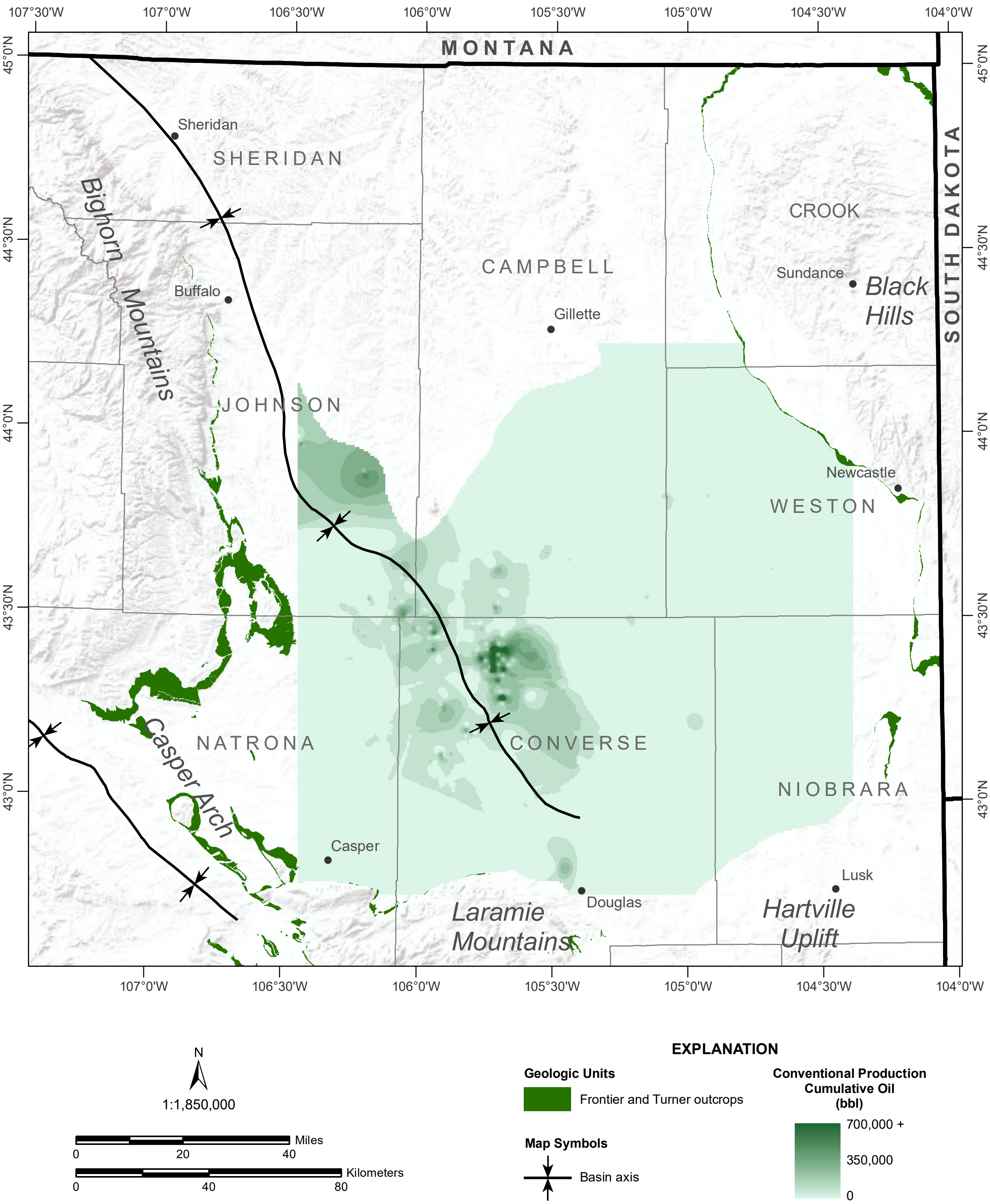

Wold Energy Partners LLC
2013
2014
2015
2017
2018
Monthly Gas (Mcf)
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

Appendix 3: Wall Creek-Turner reservoir production and geologic attributes maps

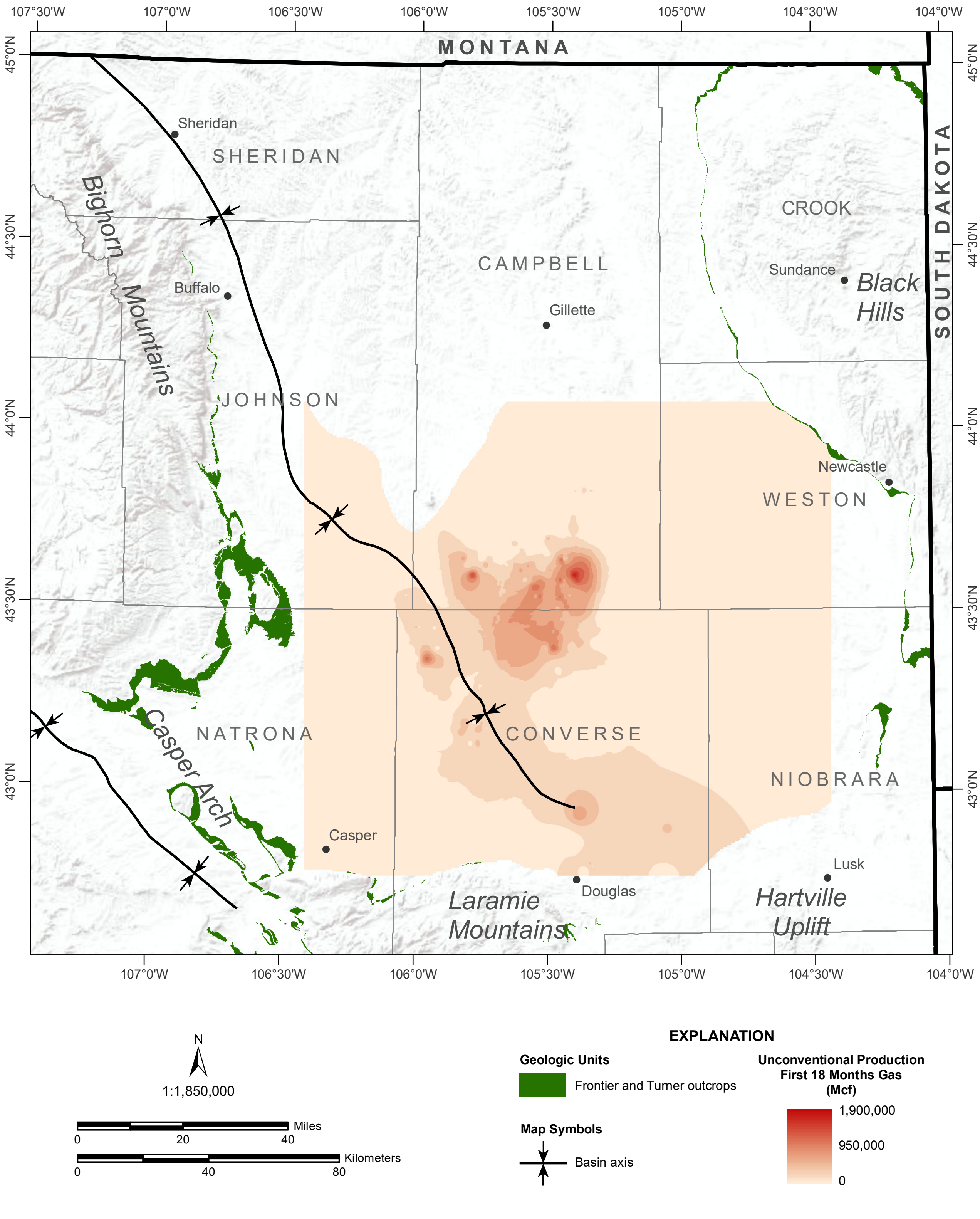
Map A3-1. Wall Creek-Turner first 18 months of unconventional oil production.



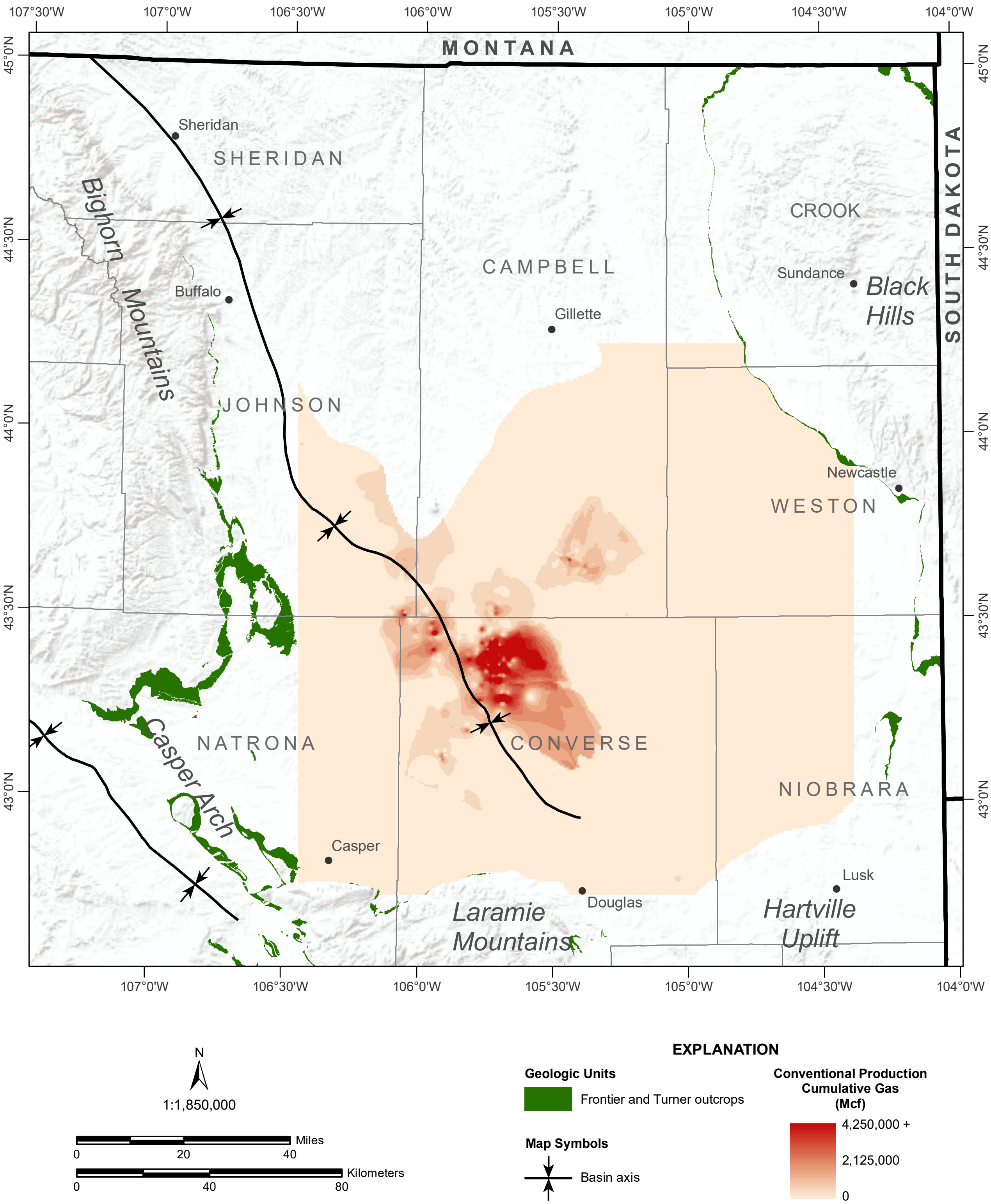
Map A3-2. Wall Creek-Turner cumulative conventional oil production.



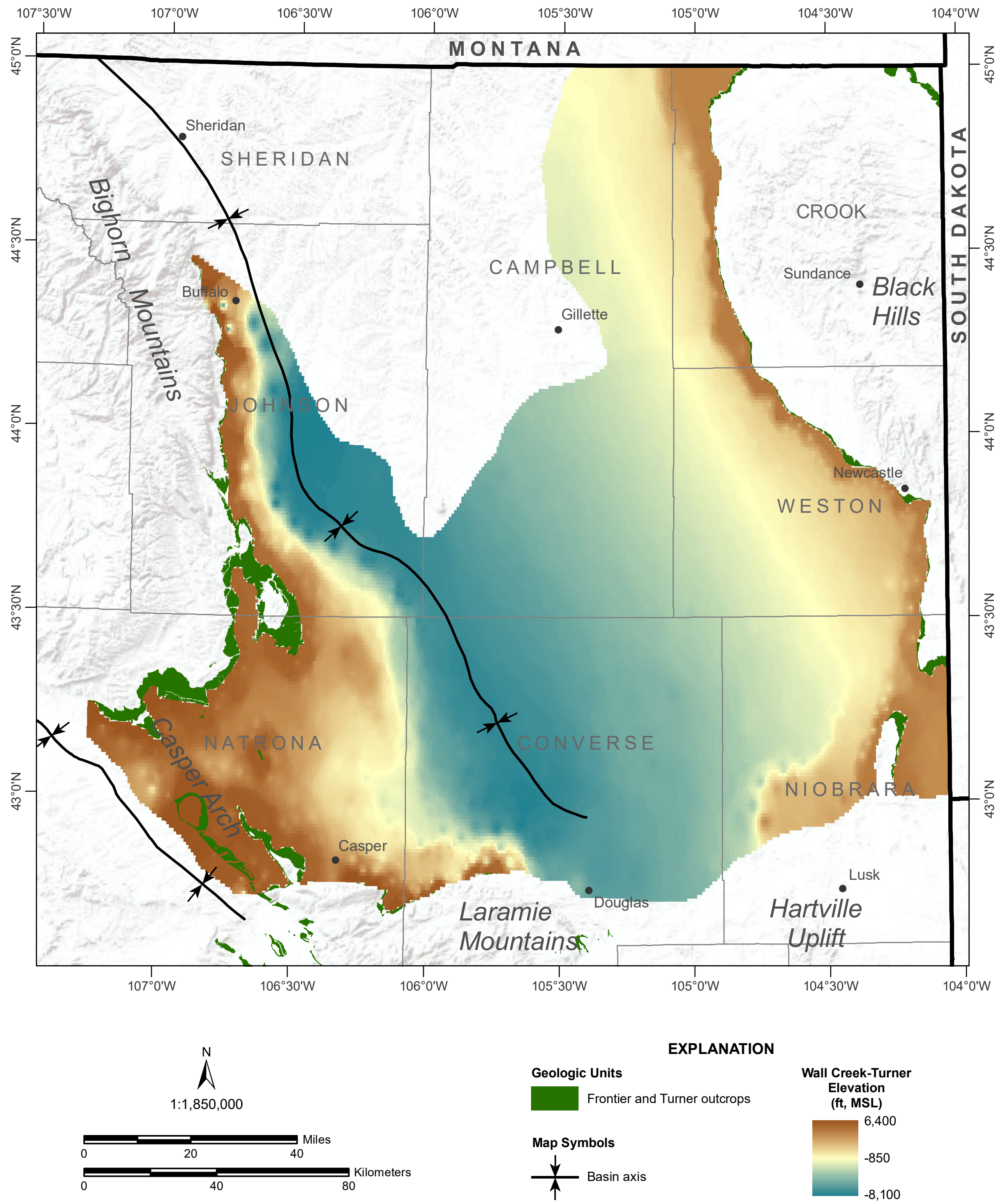
Map A3-3. Wall Creek-Turner first 18 months of unconventional gas production.



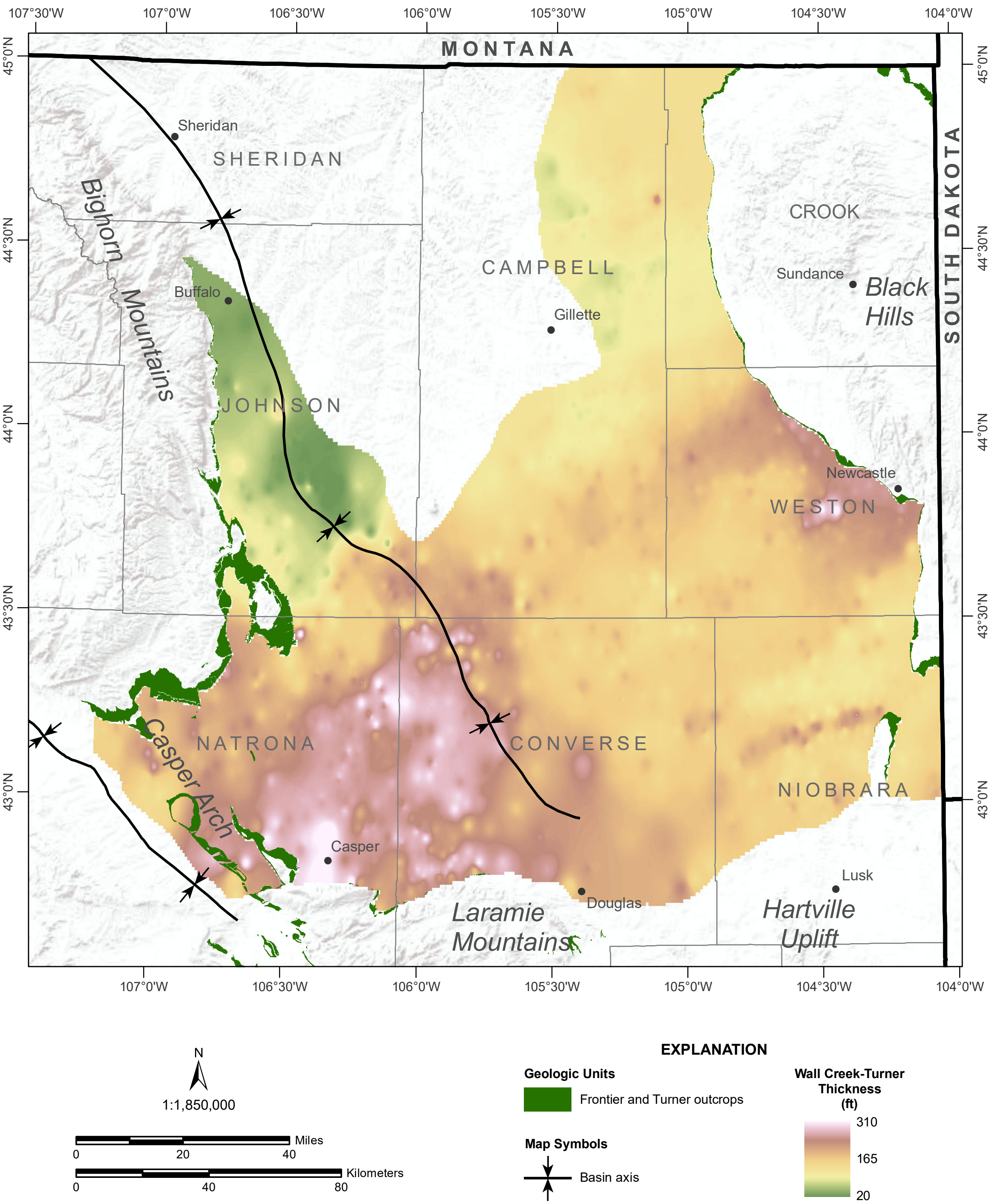
Map A3-4. Wall Creek-Turner cumulative conventional gas production.



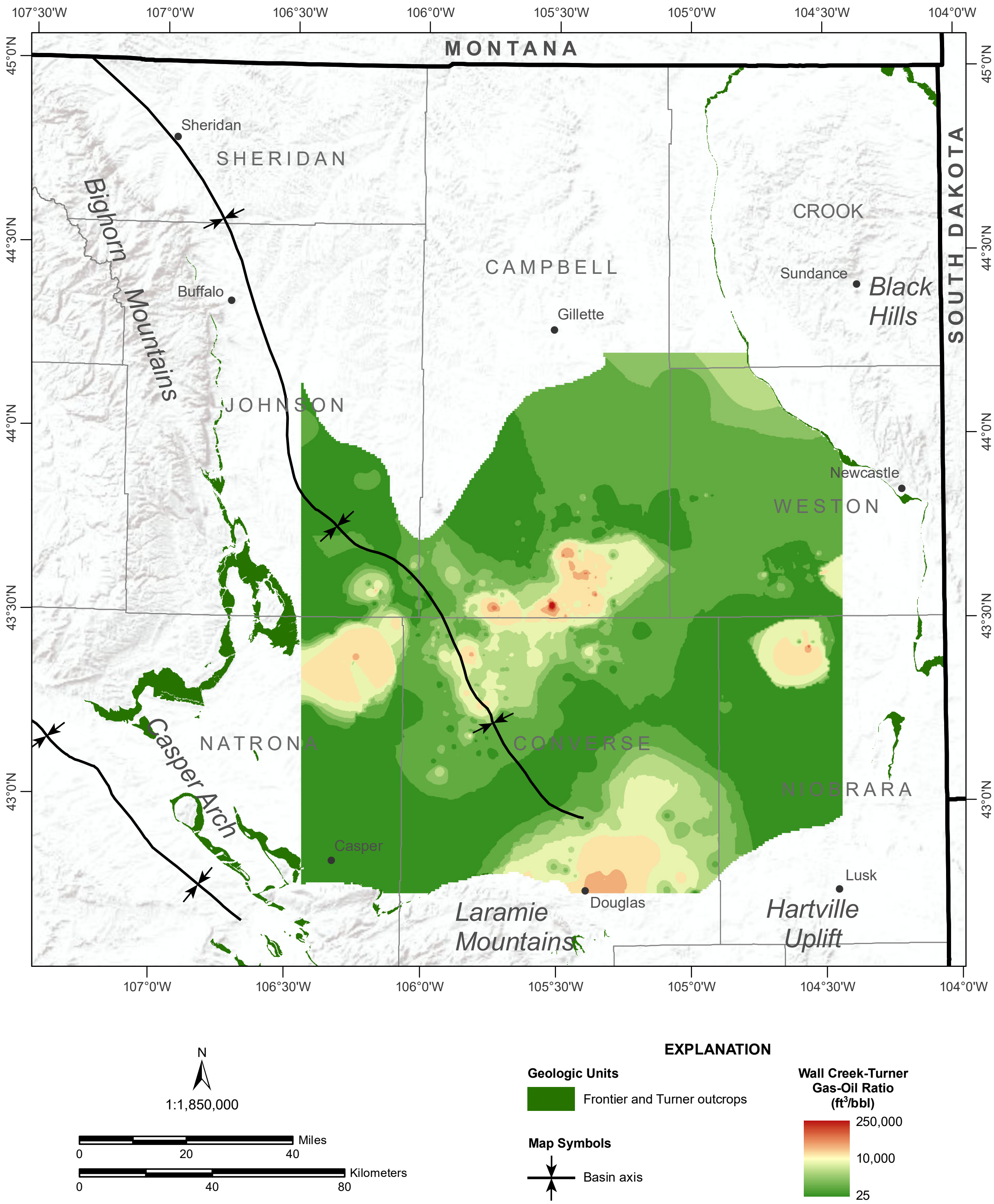
Map A3-5. Wall Creek-Turner depth to top of reservoir.



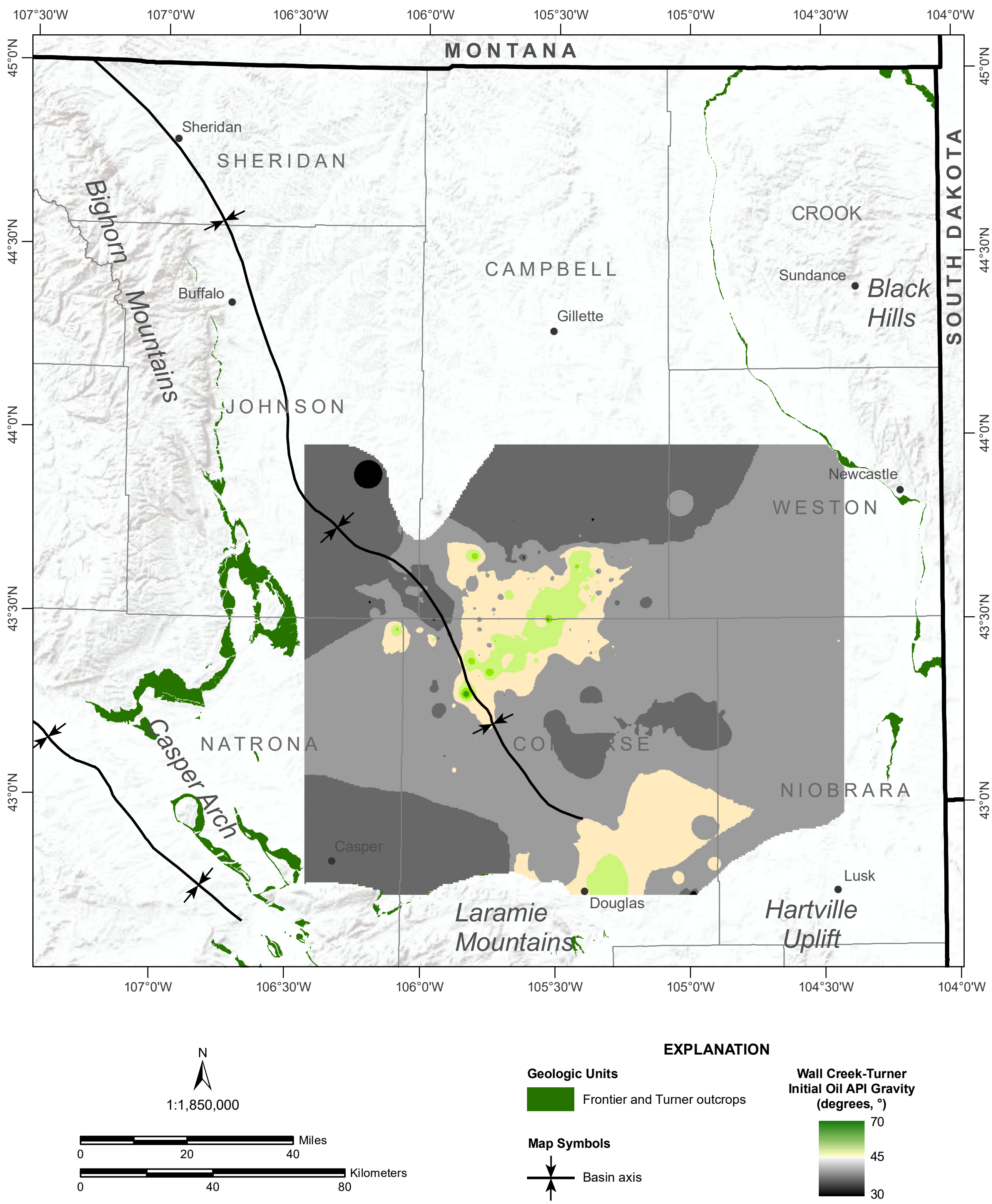
Map A3-6. Wall Creek-Turner thickness (isochore).



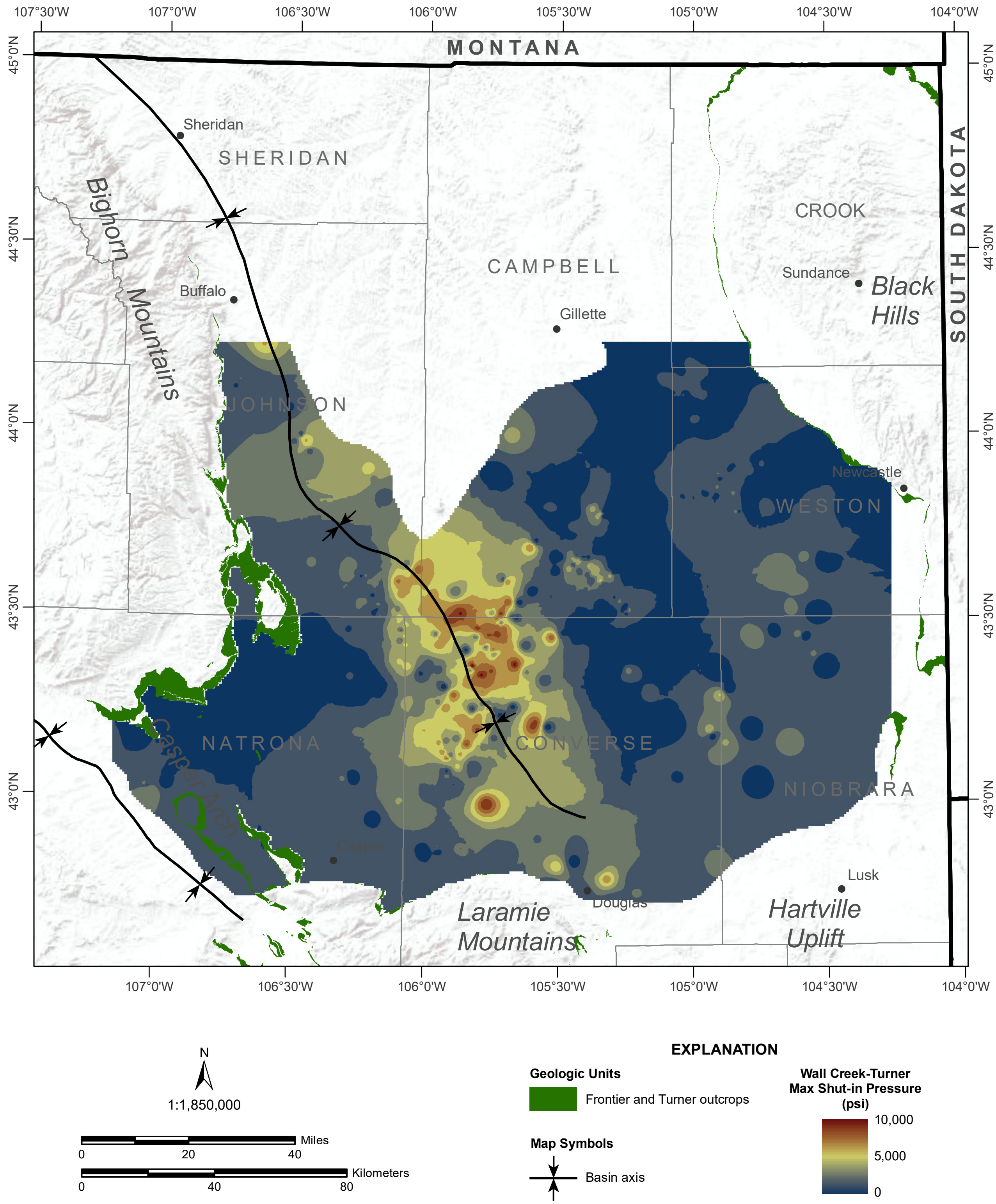
Map A3-7. Wall Creek-Turner gas-oil ratio.



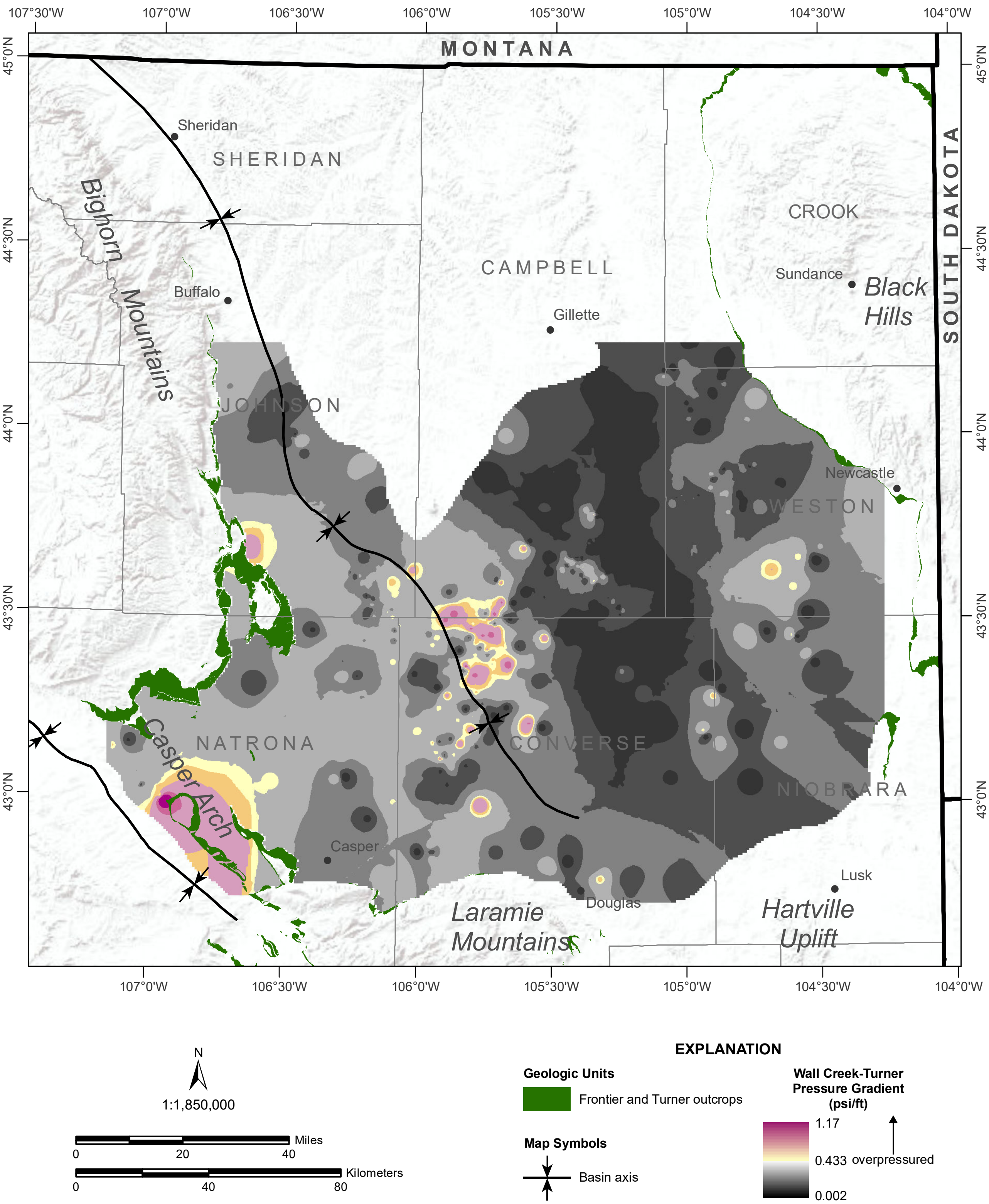
Map A3-8. Wall Creek-Turner initial crude oil API gravity.



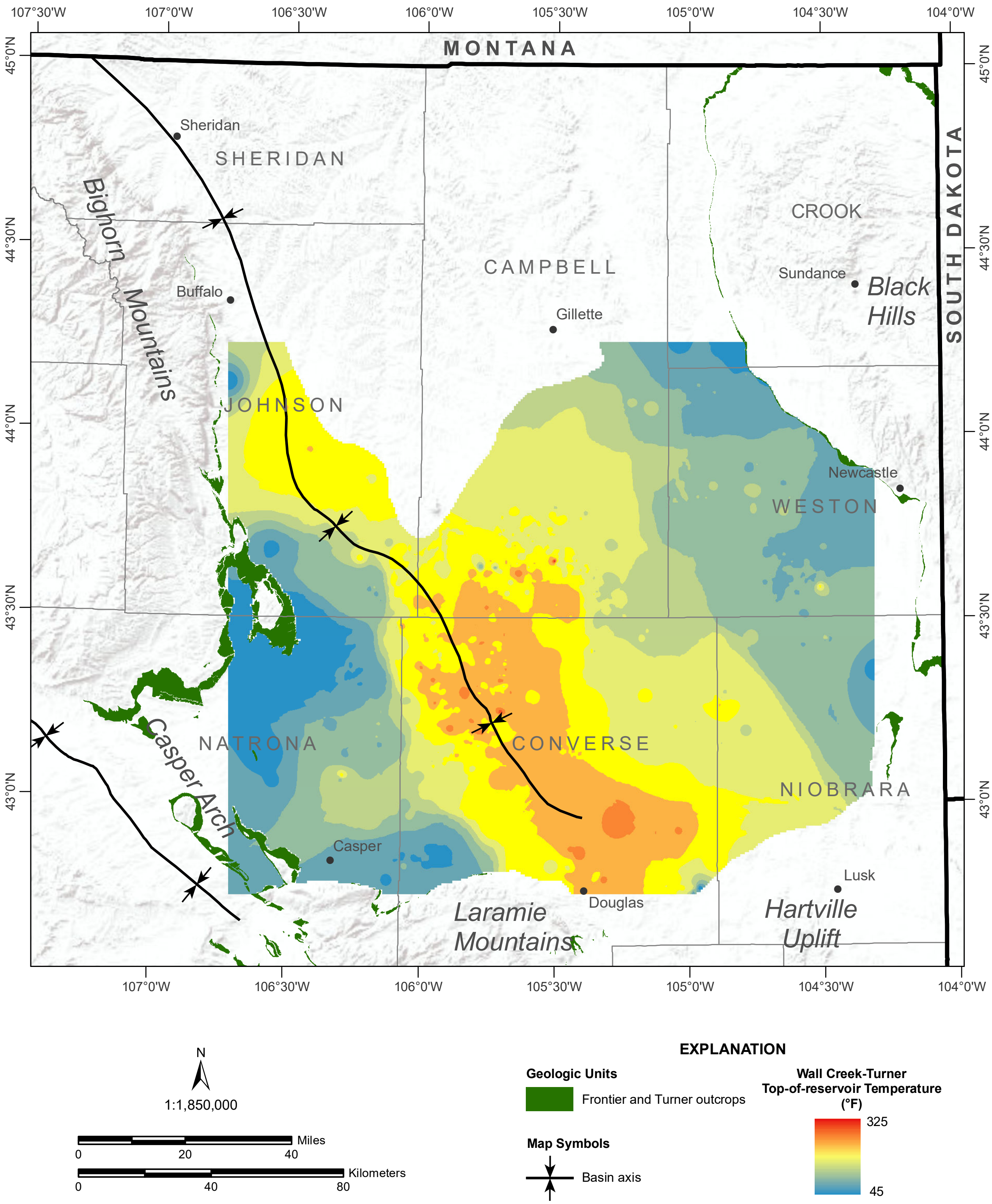
Map A3-9. Wall Creek-Turner maximum shut-in pressure.



Map A3-10. Wall Creek-Turner pressure gradient.



Map A3-11. Wall Creek-Turner top of reservoir temperature.



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