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Greater Green River Basin Formation Tops Database, Structure and Thickness Contour Maps, and Associated Well Data, with a Focus on Potential Continuous Reservoirs

Derek T. Lichtner, Matthew G. Edgin, and James R. Rodgers

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Erin A. Campbell, Director and State Geologist

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Layout by Christina D. George

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ABSTRACT

The Greater Green River Basin (GGRB) in southwestern Wyoming, northwestern Colorado, and northeastern Utah is an important region for conventional and continuous tight gas and shale oil, contributing more than half of Wyoming's natural gas production. Stratigraphic interpretations in more than 2,600 oil and gas wells in the Wyoming portion of the GGRB were compiled from reliable sources or newly correlated, with the goal of providing a publicly available, quality-controlled dataset of subsurface geologic information. This dataset encompasses most of the Phanerozoic section, from the Precambrian crystalline basement to the Eocene Green River Formation, with a focus on established and potential oil and gas reservoirs, which are primarily Cretaceous in age. Well elevation datum, location, and depth were inspected for accuracy by comparison with primary documents. Contour maps of potential and emerging continuous reservoirs illustrate regional trends in formation depth and thickness. Stratigraphic interpretations and contour data are available on the Wyoming State Geological Survey (WSGS) publications webpage and the Interactive Oil and Gas Map of Wyoming.

INTRODUCTION

Scope of Report

In 2019, 62 percent of Wyoming's natural gas and 13 percent of the state's oil was produced from the Greater Green River Basin (GGRB; WOGCC, 2021). Historically, production in the region has been from conventional, high-porosity discrete reservoirs within well-defined traps in the Mississippian Madison Limestone, Pennsylvanian–Permian Tensleep Sandstone, Triassic–Jurassic Nugget Sandstone, Lower Cretaceous Cloverly Formation (Dakota Sandstone), and Upper Cretaceous Frontier Formation, Mesaverde Group, and Lance Formation (USGS Southwestern Wyoming Province Assessment Team, 2005; Toner and others, 2020; WOGCC, 2021). Although much of the modern production in the region remains conventional, developments in hydraulic fracturing and horizontal drilling have initiated a shift in the overall focus of exploration in Wyoming toward geographically extensive, low-porosity and permeability unconventional reservoirs. In the GGRB, these potential unconventional reservoirs include the Permian Phosphoria Formation, and the Upper Cretaceous Mowry Shale, Baxter Shale, Niobrara Formation, and Lewis Shale, all of which are also source rocks for the region's conventional petroleum systems (USGS Southwestern Wyoming Province Assessment Team, 2005). In recent years several of these reservoirs, particularly the Niobrara Formation, have become burgeoning plays in geologically similar nearby Rocky Mountain basins (Dellenbach, 2016; Sonnenberg, 2018). In the GGRB, the Lewis Shale rose to among the top-five producing natural gas reservoirs in 2019 and top-five oil reservoirs in 2016 (Tables 1 and 2; WOGCC, 2021). Tight gas and condensate in significant quantities have also been produced from the Fort Union Formation (Lynds and Lichtner, 2016).

To establish a baseline subsurface dataset for the stratigraphy and geometry of these potential reservoirs, the depths to these and intervening strata were interpreted in 2,656 geophysical well logs. These depth interpretations, or "formation tops," were used to create type logs for several subregions of the GGRB, generate contour maps of formation structure and thickness for key stratigraphic intervals, and populate a publicly accessible database.

Table 1. Top oil-producing reservoirs in the GGRB in 2005 and 2019 in descending order (WOGCC, 2021).

2005	2019
Lance Formation*	Lance Formation*
Mesaverde Group	Mesaverde Group
Madison Limestone	Lewis Shale*
Tensleep Sandstone	Tensleep Sandstone
Frontier Formation	Madison Limestone
Cloverly Formation (Dakota Sandstone)	Fort Union Formation*

*Primarily natural gas liquids (condensate) associated with natural gas production.

Table 2. Top natural gas-producing reservoirs in the GGRB in 2005 and 2019 in descending order (WOGCC, 2021).

2005	2019
Lance Formation*	Lance Formation
Mesaverde Group	Mesaverde Group
Madison Limestone	Madison Limestone
Tensleep Sandstone	Lewis Shale
Frontier Formation	Tensleep Sandstone
Cloverly Formation (Dakota Sandstone)	Frontier Formation

This publication examines in detail the Wyoming portion of the GGRB. Subsurface data and geologic mapping from adjacent states were used to constrain the stratigraphy and oil and gas geology.

Geologic Setting

The Greater Green River Basin, which the U.S. Geological Survey (USGS) defines as the Southwestern Wyoming Province for the purposes of petroleum systems and geologic assessment, encompasses an area of about 60,000 km^2 (23,166 mi^2) in southwestern Wyoming, northwestern Colorado, and northeastern Utah (fig. 1). The GGRB is about 500 km (311 mi) long from its southeastern margin in Eagle County, Colorado, to its northwestern limit in Teton County, Wyoming, and is about 350 km (217 mi) wide.

To the west, the GGRB is bounded by the Sevier overthrust belt, and on all other sides by Laramide basement-cored uplifts, which are the Wind River Range and Granite Mountains to the north, Uinta Mountains and Axial Basin uplift to the south, and Rawlins uplift, Sierra Madre Range, and Park Range to the east (fig. 1). The Rock Springs Uplift and other major intrabasinal anticlines partition the GGRB into several named subbasins—the Green River, Great Divide, Washakie, and Sand Wash. Major intrabasinal anticlines include the Moxa arch (and LaBarge platform), Pinedale anticline, Wamsutter arch, and Cherokee Ridge arch. The general trend of geologic structures is north–south, with the exception of the Uinta Mountains, Wamsutter arch, Cherokee Ridge arch, Granite Mountains uplift, and Sand Wash Basin, which trend east–west, and the Wind River Range and Axial Basin uplift, which trend northwest.

Where structural relief is at its greatest, the GGRB contains more than 10,600 m (34,777 ft) of Cambrian- to Quaternary-age sedimentary deposits (figs. 2 and 3; Blackstone, 1993; Law, 1996; Loveland and others, in press). The Paleozoic section, which comprises about one-fourth to one-third of the total sedimentary thickness, was deposited along the passive western margin of the North American craton (Boyd, 1993), after which a modest volume of Triassic and Jurassic strata were deposited in a variety of marginal marine and non-marine environments (Picard, 1993).

The thickest stratigraphic interval in the GGRB is the Cretaceous section, which in some locations exceeds 4,500 m (14,764 ft). During much of the Cretaceous, fluctuations in relative sea level and sediment supply, combined with the abundant accommodation space provided by Sevier deformation, preserved a thick, complex sequence of intercalated shallow marine, deltaic, and coastal sediments throughout much of western and central North America (Royse, 1993; Steidtmann, 1993).

Near the end of the Cretaceous and into the Eocene, Laramide deformation produced in large part the modern structural configuration of the GGRB, partitioning the Sevier foreland in Wyoming into discrete basins separated by Laramide uplifts (Brown, 1993). In the uppermost GGRB Cretaceous strata, the Laramide orogeny manifests as a transition in depositional environment from primarily marine and coastal to intracontinental alluvial and lacustrine settings.

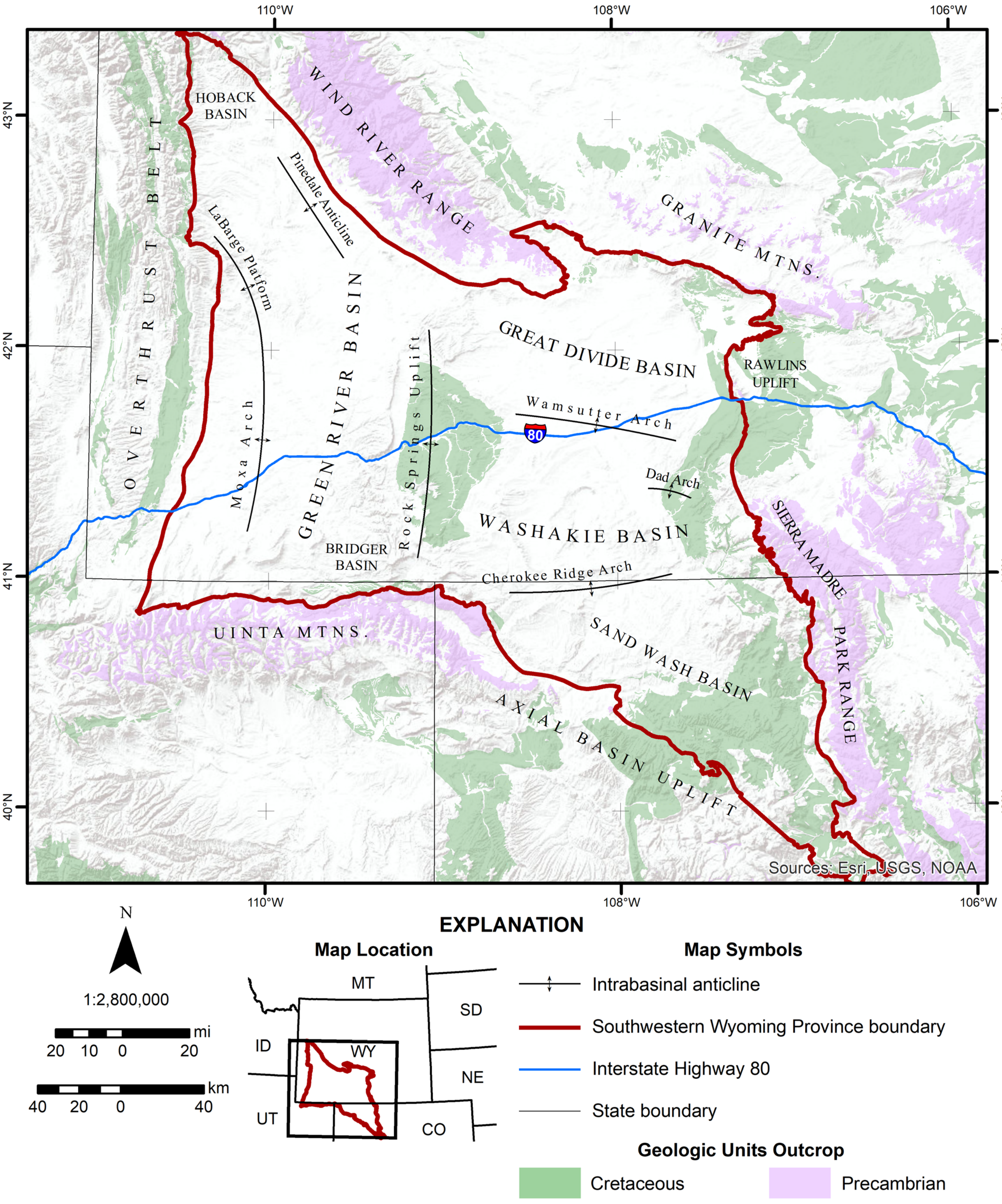

Figure 1. Map of the Greater Green River Basin, subbasins, intrabasinal anticlines, and surrounding uplifts.

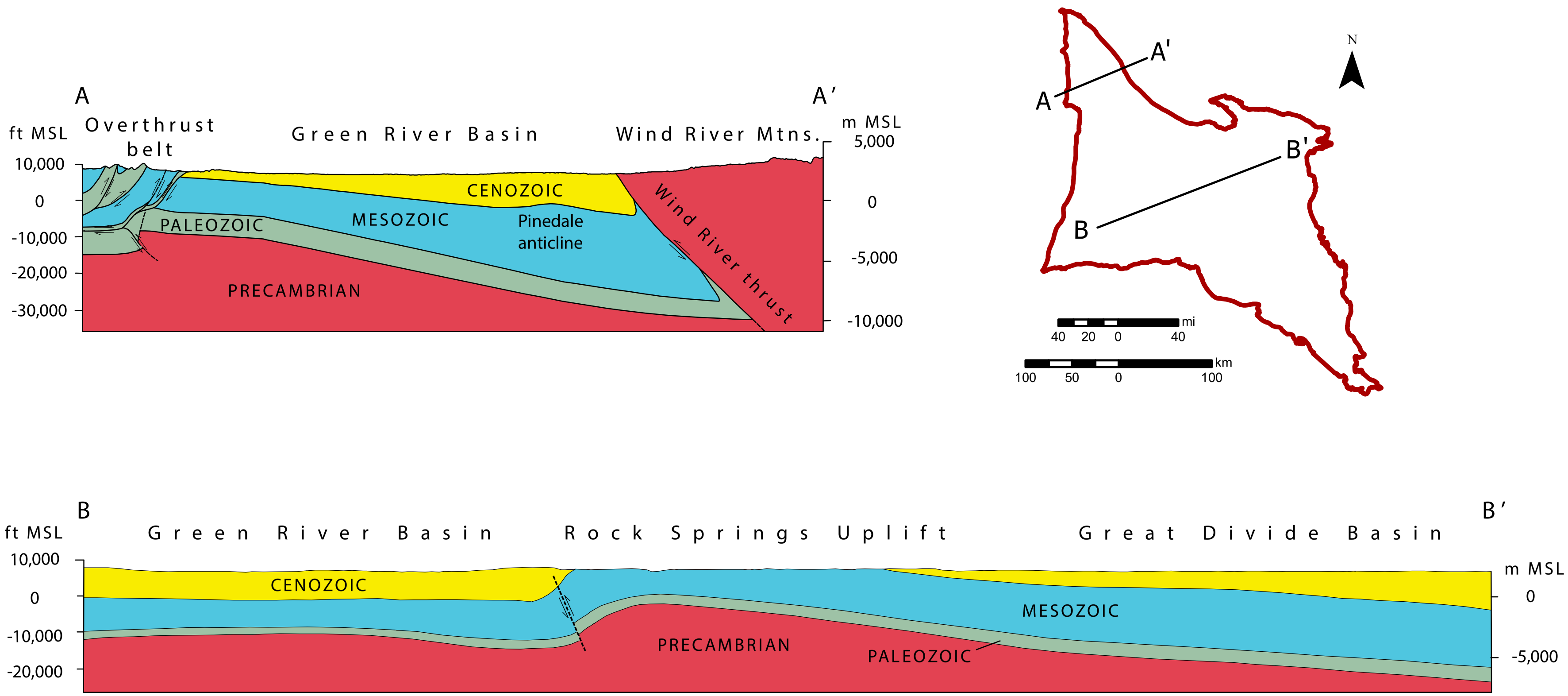

Figure 2. Generalized cross sections of the Greater Green River Basin, after Root and others (1973) and Stone (1987).

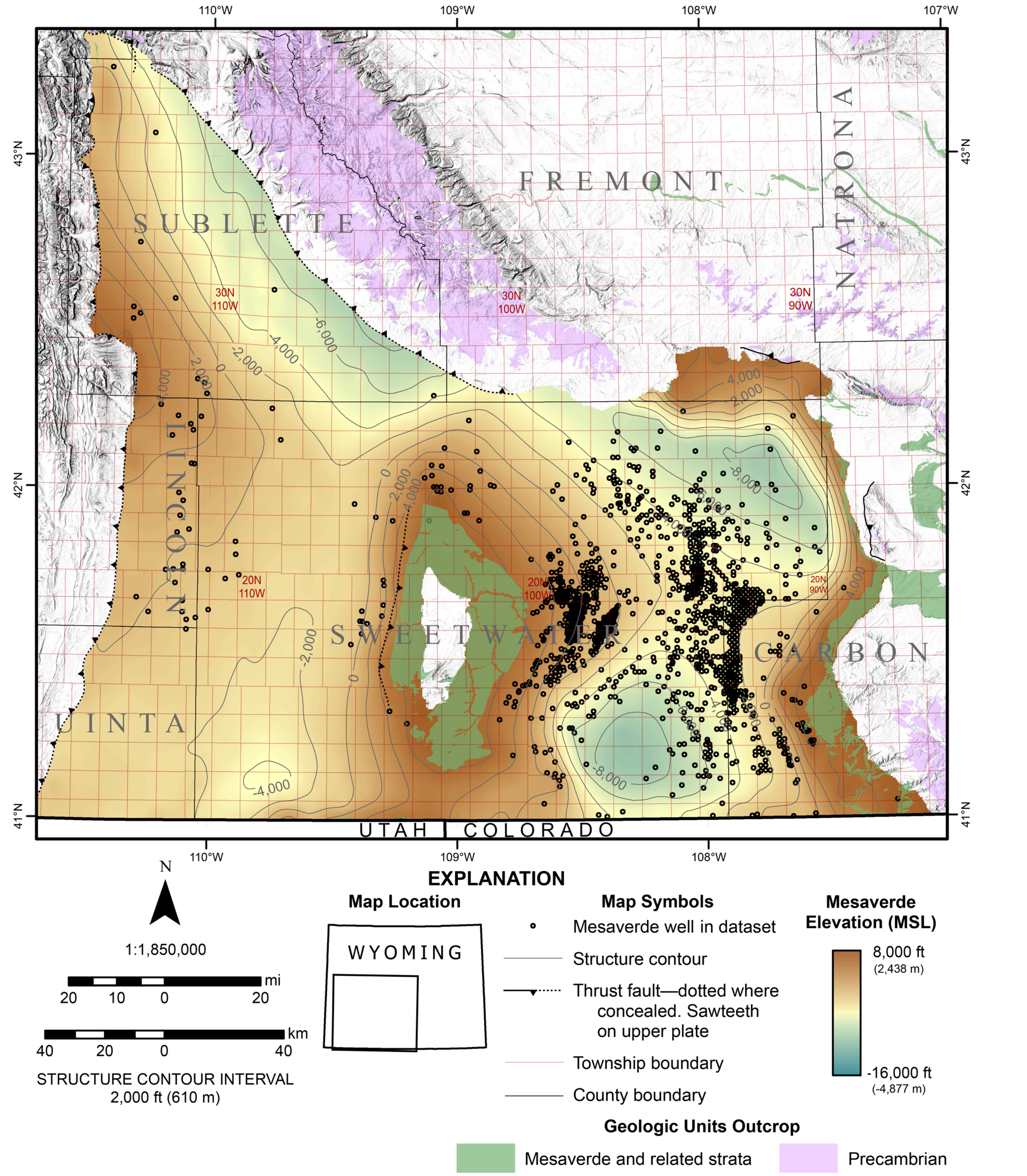

Figure 3. Elevation of the top of the Upper Cretaceous Mesaverde Group.

The remaining sedimentary thickness consists of predominantly intracontinental deposits of Paleocene and Eocene age (Lillegraven, 1993). Based on thermal maturity data and preserved remnants of younger deposits, it is hypothesized that the region was buried during late Eocene to Miocene time with up to an additional 1,200 m (3,937 ft) of volcaniclastic sediments (Mears, 1993). From the Miocene to present, erosion sculpted the region's modern day topography.

Descriptions of Select Stratigraphic Intervals

Several of the intervals for which subsurface correlations were made are potential or emerging continuous oil and gas reservoirs. The depositional history and hydrocarbon potential of these select stratigraphic intervals are summarized below.

Phosphoria Formation

The Permian Phosphoria Formation is composed of black shale, chert, and carbonate rock, with minor siltstone and sandstone (Sheldon, 1963; Carnes, 2015). The Phosphoria Formation was deposited approximately 269–265 million years ago off the northwestern coast of Pangea, in the former Sublett Basin, which corresponds to parts of modern day western Wyoming, southeastern Idaho, southwestern Montana, and northeastern Utah (Maughan, 1984). The Sublett Basin was bounded to the north by the Milk River uplift of western Montana, to the south by the Ancestral Rocky Mountains and the Confusion Shelf in Colorado, and to the east by the evaporative Goose Egg Basin (Maughan, 1984; Wardlaw and others, 1995; Perkins and others, 2003; Hein, 2004). To the east, southeast, and south of its depocenter, and throughout much of the GGRB, the Phosphoria Formation intertongues with the carbonate shelf deposits of the Park City Formation. In west-central Wyoming, driller nomenclature often refers to this complex interval of intertonguing lithologies as simply the Phosphoria Formation (Boyd, 1993; Johnson, 2005). In the easternmost GGRB, these lithologies intertongue with the red beds of the Goose Egg Formation. The Phosphoria Formation unconformably overlies the Pennsylvanian–Permian Tensleep-Weber sandstones and is unconformably overlain by the Triassic Dinwoody Formation.

In Wyoming the Phosphoria Formation consists of five units—a lower unnamed chert member, and the Meade Peak, Rex Chert, Retort, and Tosi Chert members (Sheldon, 1963). The Meade Peak and Retort members are considered the primary petroleum source rocks for sub-Cretaceous reservoirs in the GGRB as well as potential self-contained continuous natural gas reservoirs (Johnson, 2005; Schenk and others, 2019).

The Meade Peak Member of the Phosphoria Formation is a dark-colored shale interbedded with phosphorite, muddy siltstone, carbonate rock, and minor sandstone. It obtains a maximum thickness of approximately 75 m (246 ft) in southeastern Idaho, northeastern Utah, and southwestern Wyoming (Sheldon, 1967; Tisoncik, 1984). To the east, the Meade Peak Member thins and become sandier, grading into the lower unnamed chert and Rex Chert members. The Retort Member, a similarly composed black shale, is separated from the underlying Meade Peak Member by the intervening Rex Chert Member. The Retort Member has a maximum thickness of approximately 25 m (82 ft) in southwestern Montana.

The Meade Peak and Retort members are both oil-prone source rocks containing marine Type-IIS kerogen (Johnson, 2005; Schenk and others, 2019). The total organic carbon (TOC) content of the Meade Peak Member averages 2.4 weight percent, with a maximum of approximately 9 weight percent in southeastern Idaho (Johnson, 2005). The average TOC of the Retort Member is approximately 4.9 weight percent, with an average maximum of 10 weight percent in southwestern Montana. The most organic-rich beds in these members exhibit TOC as high as 30 weight percent (Maughan, 1984).

The Phosphoria Formation is thermally overmature in the overthrust belt and undermature in southwestern Montana, where, at the Retort Member's type locality, it contains oil shale (Johnson, 2005). In the GGRB, the thermal maturity of the Phosphoria Formation ranges from within the dry gas window to postmature (Edman and Surdam, 1984; Burtner and Nigrini, 1994). The timing of oil generation in the Phosphoria Formation has been the subject of debate (Stone, 1967; Claypool and others, 1978; Burtner and Nigrini, 1994). In general, the Phosphoria is thought to have reached burial depths sufficient for oil generation sometime in the Mesozoic to Early Cretaceous in the overthrust belt and in the Late Cretaceous in the GGRB. Prior to Laramide deformation, Phosphoria-sourced oil from the overthust belt migrated eastward throughout the Rocky Mountain region, supplying many of the sub-Cretaceous conventional reservoirs in the GGRB (Sheldon, 1967; Johnson, 2005). Although Johnson (2005) suggested that most production reported from the Phosphoria Formation itself in the GGRB is actually from intertonguing Park City Formation carbonates and that no continuous accumulations exist below the Cretaceous in the GGRB, data from the Moxa arch suggest the Phosphoria Formation may produce shale gas (Stilwell, 1989). Schenk and others (2019) estimated that the Phosphoria in the GGRB contains 1.4 trillion cubic feet of undiscovered, technically recoverable natural gas.

Mowry Shale

The Upper Cretaceous (Cenomanian) Mowry Shale in the GGRB consists of several hundred feet of organic-rich, siliceous, dark-colored shale with minor beds of siltstone and sandstone (Davis, 1970; Kirschbaum and Mercier, 2013). It was deposited during maximum marine transgression in the cool, anoxic waters of a restricted sea that extended from the Artic to Colorado (Byers and Larson, 1979). The silica in the Mowry Shale is hypothesized to be biogenic (Davis, 1970). Bentonite beds are common and clearly visible in geophysical well logs, and can aid in subsurface correlation. Coarse-grained sediment input increases upsection and westward, as does the degree of bioturbation, suggesting shallower waters.

The Mowry Shale crops out throughout most of Wyoming and parts of surrounding states. The siliceous shale of the Mowry is underlain by an interval of nonsiliceous black shale sometimes called the Shell Creek Shale, which is sometimes grouped with the Mowry. For the purposes of this study in the GGRB, the Shell Creek Shale is considered part of the Mowry Shale interval (Lynds and Slattery, 2017). The combined Mowry-Shell Creek Shale is conformably underlain by the Lower Cretaceous Muddy Sandstone. The top of the Mowry is marked by the geographically extensive Clay Spur bentonite bed, which is conformably overlain by the Upper Cretaceous Frontier Formation. In the overthrust belt, the Mowry Shale is equivalent to the Aspen Shale. These names are often used interchangeably in the westernmost GGRB.

The Mowry Shale is an important source rock throughout the region, and in the GGRB is considered the primary source rock for conventional hydrocarbon accumulations in the overlying Frontier Formation (Burtner and Warner, 1984). TOC measurements of the Mowry Shale in the GGRB range from 1.2 to 2.5 weight percent; however, it is thought that these measurements may underestimate actual TOC due to expulsion of carbon dioxide and hydrocarbons from the samples during burial (Burtner and Warner, 1984; Kirschbaum and Roberts, 2005). The Mowry Shale contains both Type-II and Type-III kerogen, with gas-prone Type-III source rocks more common to the west. In the overthrust belt, petroleum generation in the Mowry likely began in the early Late Cretaceous, prior to the development of the Hogsback and Prospect thrusts, thereby allowing for migration eastward into Frontier Formation sandstones in the GGRB (Kirschbaum and Roberts, 2005). Within the GGRB, petroleum generation began in the Late Cretaceous in the deep Washakie Basin and the mid-Eocene on the Moxa arch (Dutton and Hamlin, 1992; Kirschbaum and Roberts, 2005).

Unconventional production from continuous accumulations in the Mowry Shale is centered on the Moxa arch, where reservoir quality is reported to depend on fracturing and faulting (Dutton and Hamlin, 1992; Anderson and Dietz, 2003), as well as depositional environment and diagenetic history (Stonecipher and others, 1984; Stonecipher and Diedrich, 1993). The USGS petroleum system assessment of continuous accumulations in the Mowry Shale in the GGRB estimated a mean of 8,542 billion cubic feet of undiscovered, technically recoverable natural gas and 171 million barrels of natural gas liquids (Kirschbaum and Roberts, 2005).

Baxter Shale

The Upper Cretaceous (Coniacian through lower Campanian) Baxter Shale was deposited in the Western Interior Seaway, and consists of about one thousand meters (several thousand feet) of dark-colored shale interbedded with locally correlative, coarsening-upward siltstones and sandstones (Finn and Johnson, 2005b). In the western GGRB, the overthrust belt name Hilliard Shale is sometimes substituted for the Baxter Shale, and in the Rock Springs Uplift, the Colorado name Mancos Shale is sometimes used. Although the Baxter Shale is equivalent to parts of the Mancos, Cody, Steele, Hilliard, and Pierre shales, various intertonguing sandstones of Baxter and Mesaverde age complicate the nomenclature (Gill and Cobban, 1973; Lynds and Slattery, 2017). Except for in the eastern GGRB, where carbonates of the Niobrara Formation are present, this thick, mostly Coniacian and Santonian interval of marine shale will in this publication be simply referred to as the Baxter Shale.

The Baxter Shale is conformably underlain by the Frontier Formation throughout the GGRB. The top of the Baxter Shale is defined as the conformable contact with the base of the lowermost marginal-marine sandstone of the Mesaverde Group, which in the Rock Springs Uplift is the Blair Formation; in the western GGRB where the Blair Formation is absent, the Rock Springs Formation; and in the eastern GGRB, the Haystack Mountains Formation (Lynds and Slattery, 2017). Because of the intertonguing relationships of these sandstones and the Baxter Shale, the age of the contact between the Baxter Shale and overlying Mesaverde Group is up to several million years older in the western GGRB than in the eastern GGRB.

Measurements of TOC in the Baxter Shale range from 0.25 to 2.71 weight percent, and are typically at the higher end of that range in the shales compared to in the siltstones (Law, 1984; Finn and Johnson, 2005b; Longman and others, 2016). The organic matter within the Baxter Shale is both Type-II and Type-III (U.S. Geological Survey, 2009). The Baxter Shale is thermally mature to very mature throughout most of the GGRB, with the exception of the basin margins, Rock Springs Uplift, and LaBarge platform. Onset of hydrocarbon generation at the base of the Baxter Shale is modeled to have occurred in the Late Cretaceous in the deep Washakie Basin to early Eocene in the Green River Basin (Finn and Johnson, 2005b).

The shale gas potential of the Baxter Shale has been a subject of debate. Novosel and others (2011) assert that the Baxter Shale is typically not a quality source rock, and that its TOC is too low compared to its thickness for the generation of significant volumes of petroleum. Longman and others (2016), however, demonstrate some success in producing from the Baxter in the Canyon Creek field near the Wyoming-Colorado border, and suggest that, with the development of newer well completion technology (the most recent wells they examine were completed in 2008), the Baxter is a potentially significant continuous gas reservoir. The USGS petroleum system assessment of continuous accumulations in the Hilliard-Baxter-Mancos shales in the GGRB estimated a mean of 11.8 trillion cubic feet of undiscovered, technically recoverable natural gas and 752 million barrels of natural gas liquids (Finn and Johnson, 2005b).

Niobrara Formation

The Upper Cretaceous (Coniacian through Santonian) Niobrara Formation is composed of marine carbonates and calcareous shales (Dellenbach, 2016). It is present in the eastern GGRB and grades westward into the noncalcareous shales of the lower Baxter Shale (Lynds and Slattery, 2017). The Niobrara Formation is conformably underlain by the Frontier Formation and conformably overlain by the Steele Shale, which is equivalent to portions of the upper Baxter Shale. The Niobrara carbonates pinch out in the Great Divide and Washakie basins, west of which the Baxter Shale and its equivalents directly overly the Frontier Formation (Finn and Johnson, 2005a; Lynds and Slattery, 2017).

Like the Baxter Shale, the Niobrara Formation was deposited in the Western Interior Seaway. Cyclic transgressions deposited distinct chalk intervals, which are typically the target reservoirs (Vincelette and Foster, 1992; Finn and Johnson, 2005a; Dellenbach, 2016). In general, Niobrara chalks grade westward into marls, and eventually disappear. These chalk and marl "benches," as they are often called, have been correlated throughout much of the Rocky Mountain region; however, the nomenclature varies. The informal names of the Buck Peak, Tow Creek, Wolf Mountain, and Rangely benches in the Sand Wash Basin of the southeastern GGRB in Colorado are considered equivalents of the A Chalk, B Chalk, C Chalk, and C Marl in the Denver Basin, respectively (Vincelette and Foster, 1992; Finn and Johnson, 2005a; Dellenbach, 2016). In the Wyoming portion of the GGRB, these benches are unnamed. Along the eastern margin of the Washakie Basin in Carbon County, Wyoming, Lichtner and others (2017) made preliminary correlations of outcrops of Niobrara Formation with the Buck Peak, Tow Creek, and Wolf Mountain benches.

Maximum TOC preservation and carbonate deposition are associated with the Buck Peak and Tow Creek benches, which are considered fair to good quality source rocks and reservoirs in the Sand Wash Basin (Dellenbach, 2016). TOC measurements in the Sand Wash Basin typically range from 1 to 4 weight percent, and may be as high as 6 weight percent (Finn and Johnson, 2005a; Dellenbach, 2016). Type-II organic matter is common, but Type-III is also present (Finn and Johnson, 2005a). In addition to their high TOC, the benches exhibit high carbonate content associated with favorable brittleness characteristics for both natural and hydraulic fracturing. The thermal maturity of the Niobrara Formation increases from the eastern margin of the GGRB, where oil has historically been produced from natural fracture swarms, to the deeper Sand Wash and Washakie basins to the west, where potential wet gas and dry gas plays exist (Finn and Johnson, 2005a; Cumella and others, 2014; Dellenbach, 2016).

The USGS petroleum system assessment of continuous accumulations in the Niobrara Formation in the GGRB estimated a mean of 103.6 million barrels of oil and 62.2 billion cubic feet of gas (Finn and Johnson, 2005a). This total does not include potential deeper, basin-centered continuous gas accumulations due to a lack of data in the central Sand Wash and Washakie basins.

Lewis Shale

The Upper Cretaceous (Maastrichtian) Lewis Shale consists of several thousand feet (up to about 1,000 m) of dark-colored shale interbedded with sandstone and siltstone (Asquith, 1970; Roehler, 1993). Deposition occurred in a westward embayment of the Western Interior Seaway during its final major transgression prior to the regional transition to terrestrial sedimentation (Gill and others, 1970). The Lewis Shale is present throughout the Great Divide, Sand Wash, and Washakie basins, and is absent on the western flank of the Rock Springs Uplift and in the vicinity of the Granite Mountains uplift. It is conformably underlain by the Mesaverde Group and is conformably overlain by, and interfingers with, the Fox Hills Sandstone (Lynds and Slattery, 2017). In the eastern Washakie Basin, the Lewis Shale is divided into lower and upper shales by the Dad Sandstone Member, which is up to 425 m (1,394 ft) thick at its depocenter (Asquith, 1970). The Dad Sandstone thins to the north, west, and south, grading into undivided Lewis Shale.

In the lower part of the Lewis Shale, the Asquith marker zone, a 10- to 35-m-thick (33 to 115 ft), laterally extensive, organic-rich interval, is considered a primary source rock for gas accumulations within sandstones in the Lewis (Law, 1996; Pyles, 2000; Dolloff and Lancaster, 2001; Zainal, 2001; Hamzah, 2002). TOC measurements of the Asquith marker zone range from 1.68 to 3.15 weight percent (Pyles, 2000; Zainal, 2001). Other shale intervals within the Lewis Shale have exhibited TOC values ranging from 0.55 to 2.86 weight percent, with an average of 1.33 weight percent (Law, 1984). Organic matter within the Lewis is predominantly Type-III gas-prone (Hettinger and Roberts, 2005).

Gas generation in the deep Washakie and Sand Wash basins is modeled to have begun in the late Paleocene, with sufficient burial for peak gas generation in the early Eocene (Hettinger and Roberts, 2005). By the middle Miocene, the Lewis Shale was thermally mature and generating gas throughout most of the study area. Confidence in the existence of continuous gas accumulations in the Lewis Shale historically has been high (Law and Spencer, 1993; Law, 2002), and both oil (condensate) and gas production reported from the Lewis Shale increased from 2015 through 2019 (WOGCC, 2021). The USGS petroleum system assessment of continuous gas accumulations in the Lewis Shale in the GGRB estimated a mean of 13.5 trillion cubic feet of undiscovered, technically recoverable natural gas and 541 million barrels of natural gas liquids (Hettinger and Roberts, 2005).

METHODS

Stratigraphic interpretations were initially compiled from reliable sources. Then, to expand geographic and stratigraphic coverage, further correlations were made in additional wells. Information Handling Services (IHS) Markit Petra 4.3.0 was used for viewing depth-registered raster logs and interpreting formation tops. Three geophysical logs from different parts of the GGRB were designated as type logs, guiding further subsurface correlations. Well-log header information was inspected for accuracy before a well was used in subsurface interpretation. A relational database was populated from the stratigraphic interpretations and well-log header information. Contours maps of structure and thickness were generated for select stratigraphic intervals.

Well Data Acquisition and Quality Control

The GGRB dataset consists of new stratigraphic interpretations as well as an aggregation of data that previously were either not readily available to the public or were distributed throughout the literature. First, formation tops from older scanned scientific publications were compiled (209 wells; Burk and others, 1956; Law, 1979, 1981; Law and others, 1979; Bader and others, 1982; Markochick and others, 1982; VerPloeg and others, 1983; Honey and Hettinger, 1989; Hettinger and others, 1991; De Bruin, 1997a,b,c,d; Finn and Johnson, 2005a,b; Hettinger and Roberts, 2005; Kirschbaum and Roberts, 2005). Second, unpublished WSGS stratigraphic interpretations from the early 1990s of paper well logs were converted to digital format (1,680 wells). Third, formation tops from Lynds and Lichtner's (2016) eastern GGRB study, originally provided alongside the WSGS publication as a supplemental spreadsheet, are included in the dataset (887 wells). Lastly, to improve the geographic and stratigraphic coverage of the dataset, WSGS geologists correlated formation tops in 218 additional wells. The WSGS's 1:500,000-scale depth-to-basement map was used to inform correlation in these additional wells (Blackstone, 1993; Loveland and others, in press). Nonstandard geologic nomenclature was resolved where necessary using Wyoming stratigraphic correlation charts by Love and others (1993) and Lynds and Slattery (2017).

Well-log header information and raster images were acquired from the Wyoming Oil and Gas Conservation Commission (WOGCC) public data portal. When public logs were unavailable, logs from IHS Markit's proprietary database were used; however, no proprietary data are reported or reproduced in this publication. To ensure data quality, well locations and elevation datums were compared with digital elevation models, Public Land Survey System (PLSS) designations, and aerial imagery. Total measured depth, true vertical depth, directional survey data, bottom-hole locations, and tops data were checked for discrepancies. The elevation datums for 1,841 wells and locations for 7 wells, in addition to total vertical depths for 1,893 wells, were manually recorded from primary documents. The remaining wells' locations, depths, and datums, downloaded directly from the WOGCC's data portal, passed automated quality-control checks.

The final dataset consists of 14,853 formation tops in 2,656 wells throughout the GGRB. Although the database contains tops ranging in age from Precambrian to Eocene, Cretaceous formation tops comprise the bulk of the dataset because the interval of primary interest spans the Permian Phosphoria Formation to the Upper Cretaceous Lewis Shale, and because a majority of both established plays and potential reservoirs in the region are Upper Cretaceous in the age. Downhole temperature, and the depth at which this temperature was measured, were recorded from primary documents for a select 261 wells.

Type Logs

Three representative well logs were designated as type logs and serve as examples of the characteristic resistivity and gamma log signatures in different subregions of the GGRB: the Washakie Basin (fig. 4), Moxa arch (fig. 5), and Green River Basin (fig. 6). Five-inch resolution well-log curves were digitized in NeuraLog v2020.01.31.4. Local variations in geology or pore fluids may cause well logs to differ significantly from the nearest type log.

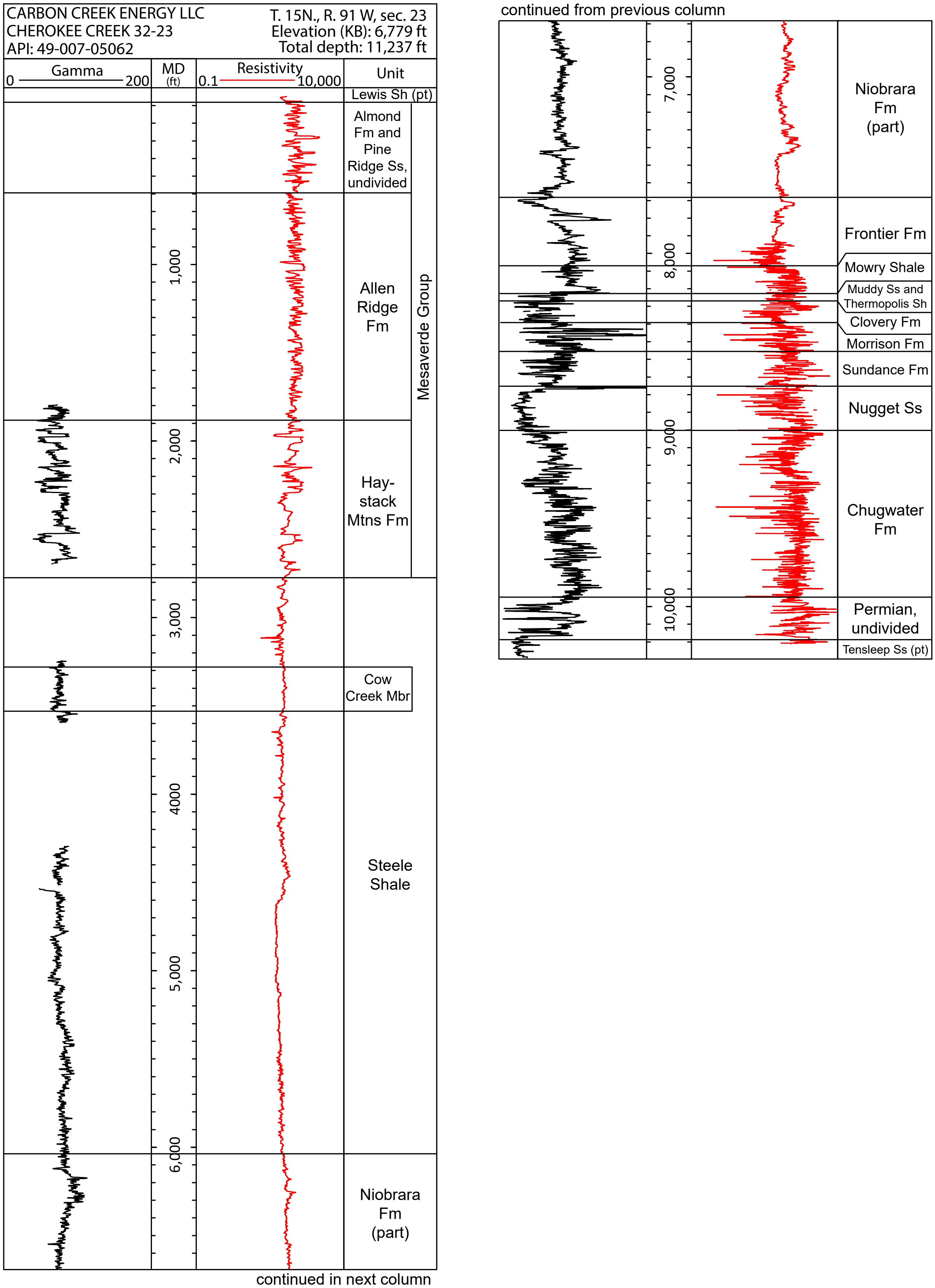

Figure 4. Type log for the eastern Greater Green River Basin, Washakie Basin. Abbreviations used are Formation (Fm), Member (Mbr), Sandstone (Ss), Shale (Sh), and part (pt).

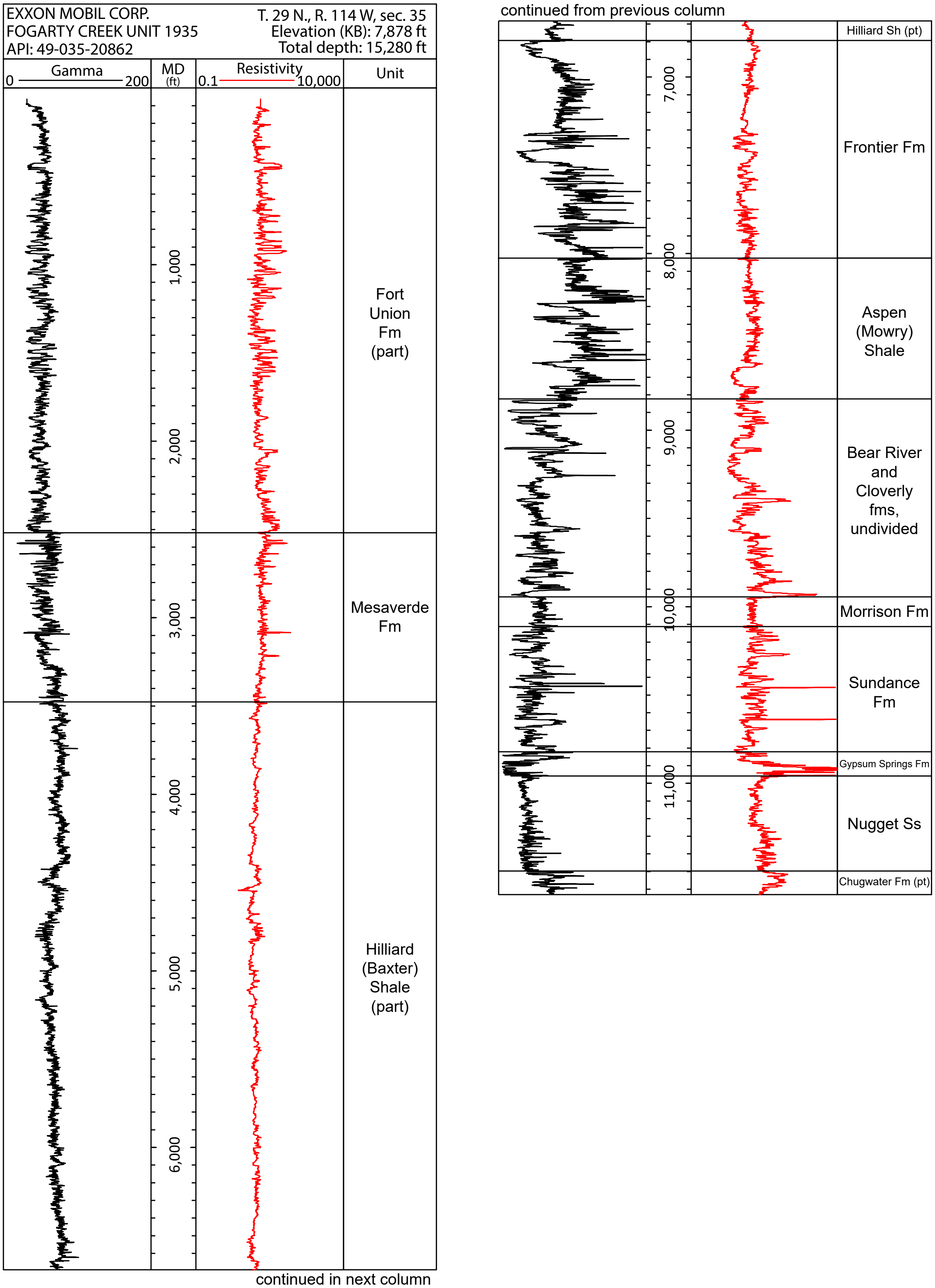

Figure 5. Type log for the western Greater Green River Basin, Moxa arch. Abbreviations used are Formation (Fm), Member (Mbr), Sandstone (Ss), Shale (Sh), and part (pt).

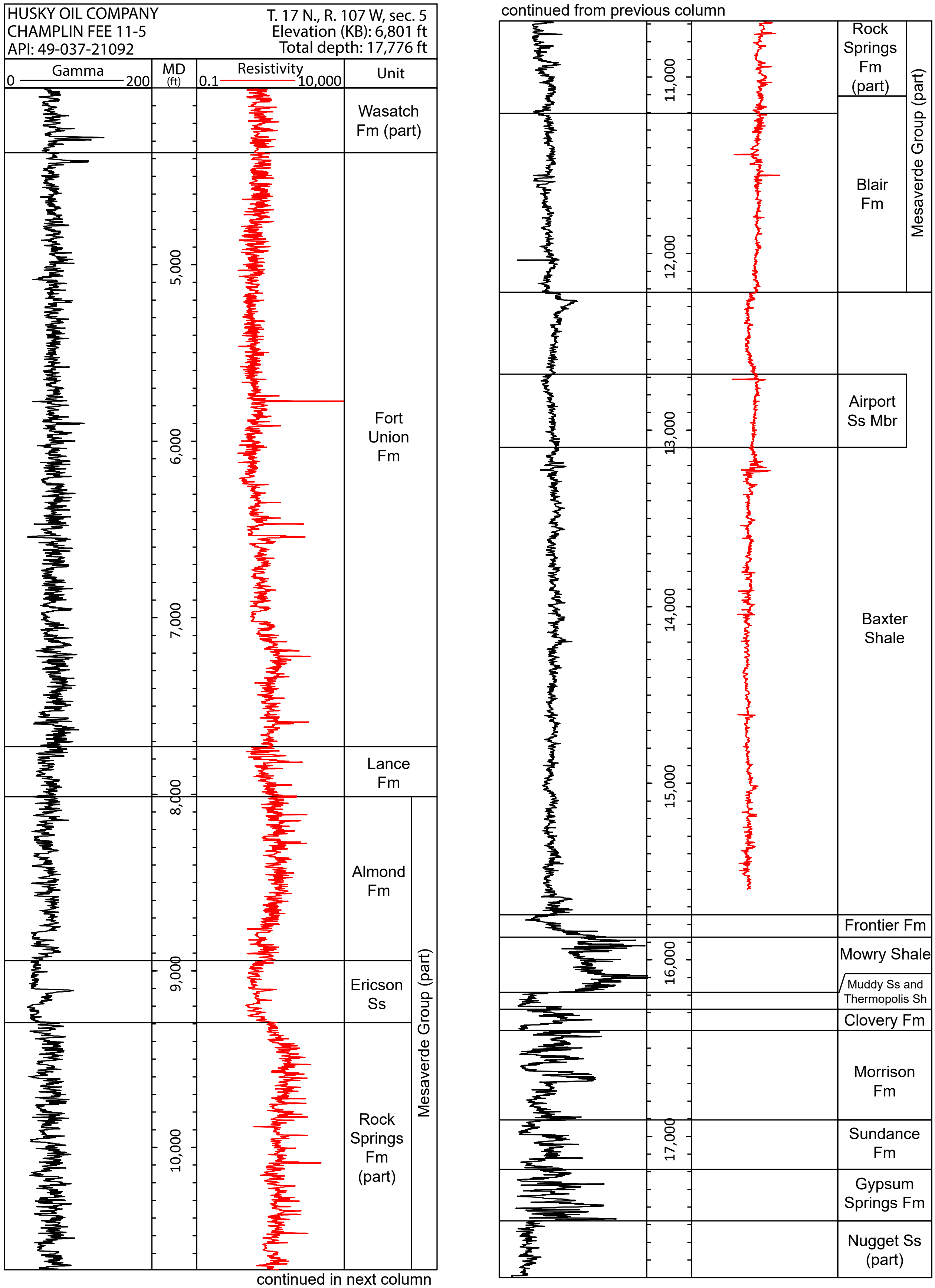

Figure 6. Type log for the central Greater Green River Basin, Green River Basin. Abbreviations used are Formation (Fm), Member (Mbr), Sandstone (Ss), and Shale (Sh).

Database

Formation tops and associated well-log header information were added to an enterprise ArcGIS Spatial Database Engine (ArcSDE). Domains were defined to maintain data input consistency, and database views were created to display complex queries and data table joins. ArcSDE, with its spatial and relational functionality, allows for organized and responsive storage and display of large datasets such as formation tops and well-log header information in the GGRB.

Contouring

To illustrate the geology of select stratigraphic intervals, contour maps were generated by interpolating formation tops and thickness between dataset wells. Top elevation relative to mean sea level (MSL) was calculated by subtracting the depth to each formation top from the elevation datum of the log, typically the kelly-bushing elevation. Formation thickness was calculated at each well and contoured using simple kriging with detrending. Because no correction was made for apparent thickness due to dip, the thickness contours are isochores. Local (Roehler, 1977, 1978, 1979; Hettinger and Honey, 2005, 2006; Gregory and Bagdonas, 2012; Carroll and others, 2015; Lynds and others, 2015; Lichtner and others, 2017), regional (Roehler, 2004; Sprinkel, 2006; Sutherland and Hausel, 2006; McLaughlin and Fruhwirth, 2008; Bryant, 2010; Jones and Scott, 2010; Jones and others, 2011; Scott and others, 2011; Sutherland and Luhr, 2011), and statewide (Tweto, 1979; Love and Christiansen, 1985) bedrock geologic maps and digital elevation models (U.S. Geological Survey, 2009) were referenced to constrain the elevation and thickness where formations intersect the ground surface.

Structure contour maps were interpolated in ArcGIS 10.7.1 using simple kriging, with detrending, of the formation top elevations (Olea, 2009; Oliver and Webster, 2014). For regions where data were scarce, such as the deep Green River and Washakie basins, a random forest machine-learning-based imputation algorithm was used to predict unknown formation depths by training the algorithm on known depths of other formations in the vicinity and their relationship to the formation for which data are missing (Stekhoven and Bühlmann, 2012). For both structure and thickness maps, the contour line overlays were smoothed for better display at the map scale.

The extent of each contour map was informed by USGS definitions of oil and gas assessment units in the GGRB, which in turn were defined by basin-bounding structures and stratigraphic pinch outs (USGS Southwestern Wyoming Province Assessment Team, 2005). The contour maps depict only the Wyoming portion of the GGRB, and exclude the Sand Wash Basin in Colorado and small areas of the Green River Basin in northeastern Utah.

Sources of Uncertainty

Uncertainty in the subsurface geologic interpretations is introduced first during data acquisition and compilation. The variability inherent in geologic process and scale also creates uncertainty, and the subsurface stratigraphy is subject to interpretation by individual geologists. Specific sources of uncertainty in this study include (1) inaccurately reported well log or completion data or incorrect original data, (2) natural well drift, (3) unresolved subsurface geologic structure, (4) steep dips and apparent thickness, (5) data clustering, and (6) geologists' interpretations. For a brief discussion of the efforts made to mitigate these factors, see Lichtner and others (2020).

In the GGRB, the confidence in structure and thickness contours is generally greatest on the Moxa arch, in the Rock Springs Uplift, and in the Great Divide and Washakie basins region, particularly on the intervening Wamsutter arch. In these regions, established oil and gas fields provide plentiful data and meso-scale structures are well known. In the deepest parts of the Green River and Washakie basins, confidence in the contour maps is relatively low, for wells penetrating the strata of interest in these regions are scarce.

STRUCTURE AND THICKNESS

General Trends

Contour maps of depth to select stratigraphic intervals in the GGRB illustrate the region's subbasins and intervening anticlinal structures. Strata are shallowest along the eastern margins of the GGRB and along the Wyoming-Utah border in the southern Green River Basin, where many formations are exposed. Various intrabasinal anticlinal structures are important for conventional and continuous hydrocarbon production, and include, in descending order of areal extent, the Rock Springs Uplift in the center of the study area, the Moxa arch and LaBarge platform in the western Green River Basin, the Wamsutter arch in the eastern GGRB (separating the Great Divide and Washakie basins), and the Pinedale anticline in the northern Green River Basin. Strata are generally deepest in the central Washakie Basin and along the Wind River thrust fault in the northern Green River Basin. The central Great Divide Basin and southern Green River Basin (sometimes called the Bridger Basin) are also local structural lows.

The thickness of units in the GGRB depends on factors too numerous and varied to discuss in detail here. For Cretaceous strata in the GGRB, factors influencing thickness may include spatial variation in subsidence rates in the Sevier foreland, intertonguing of depositional facies, and the degree of removal by erosion.

Formation Trends

Phosphoria Formation

Relatively few wells penetrate Permian strata in the GGRB, but where this occurs, the Phosphoria and Park City formations were observed. In the eastern GGRB, the Meade Peak and Retort black shale members of the Phosphoria Formation pinch out, and where present, the uppermost chert member of the Phosphoria Formation, or intertonguing carbonates of the Park City Formation or equivalents, mark the top of the Phosphoria interval.

The top of the Phosphoria Formation in the GGRB (fig. 7) is deeper than -4,800 m (-15,748 ft) MSL along the southwestern flank of the Wind River Range and about -4,500 m (-14,764 ft) deep in the central Washakie and Great Divide basins. The elevation of the Phosphoria in the study area is greatest in the northernmost Great Divide Basin, where outcrops range from 1,940 m to 2,240 m (6,365 ft to 7,349 ft). The top of the Phosphoria shallows to about -1,300 m (-4,265 ft) MSL on the LaBarge platform and 650 m (2,133 ft) MSL in the Rock Springs Uplift. Because of the complex intertonguing relationships among the Phosphoria Formation and other Permian strata, a contour map of the total thickness of the Phosphoria interval was not generated from this dataset. The thickness of black shale source rocks in the Phosphoria is shown in figure 8. The black shale facies is a maximum of 30 m (100 ft) thick in the Green River Basin, in Sublette County, Wyoming, and thins to the east, pinching out along a north–northeast trending line in the Great Divide and Washakie basins, in eastern Sweetwater County, Wyoming.

Mowry Shale

The Mowry Shale was observed throughout the GGRB. The top of the Mowry (fig. 9) ranges from deeper than -4,400 m (-14,436 ft) MSL along the southwestern flank of the Wind River Range, and about -4,200 m (-13,780 ft) MSL in the central Washakie and Great Divide basins, to 2,010–2,430 m (6,594–7,972 ft) MSL along the eastern and northeastern margins of the GGRB, where the Mowry Shale crops out. The top of the Mowry Shale shallows to approximately 90 m (295 ft) MSL on the LaBarge platform and 1,300 m (4,265 ft) MSL in the Rock Springs Uplift.

Thickness of the combined Mowry–Shell Creek shale package (fig. 10) was calculated from the top of the Mowry Shale to the top of the Muddy Sandstone. The combined Mowry and Shell Creek shales are thickest in the Green River Basin in eastern Lincoln County, Wyoming, where the combined interval exceeds 140 m (459 ft). In the overthrust belt to the west, beyond the boundaries of the study area, the interval thickens to 230 m (754 ft; Kirschbaum and Mercier, 2013). The Mowry–Shell Creek interval thins to the southeast to a study-area minimum of approximately 30 m (98 ft), in southern Carbon County, Wyoming. This thickness trend has been interpreted as the result of increased accommodation space in the western portions of the Sevier foreland due to thrust loading (Jordan, 1981).

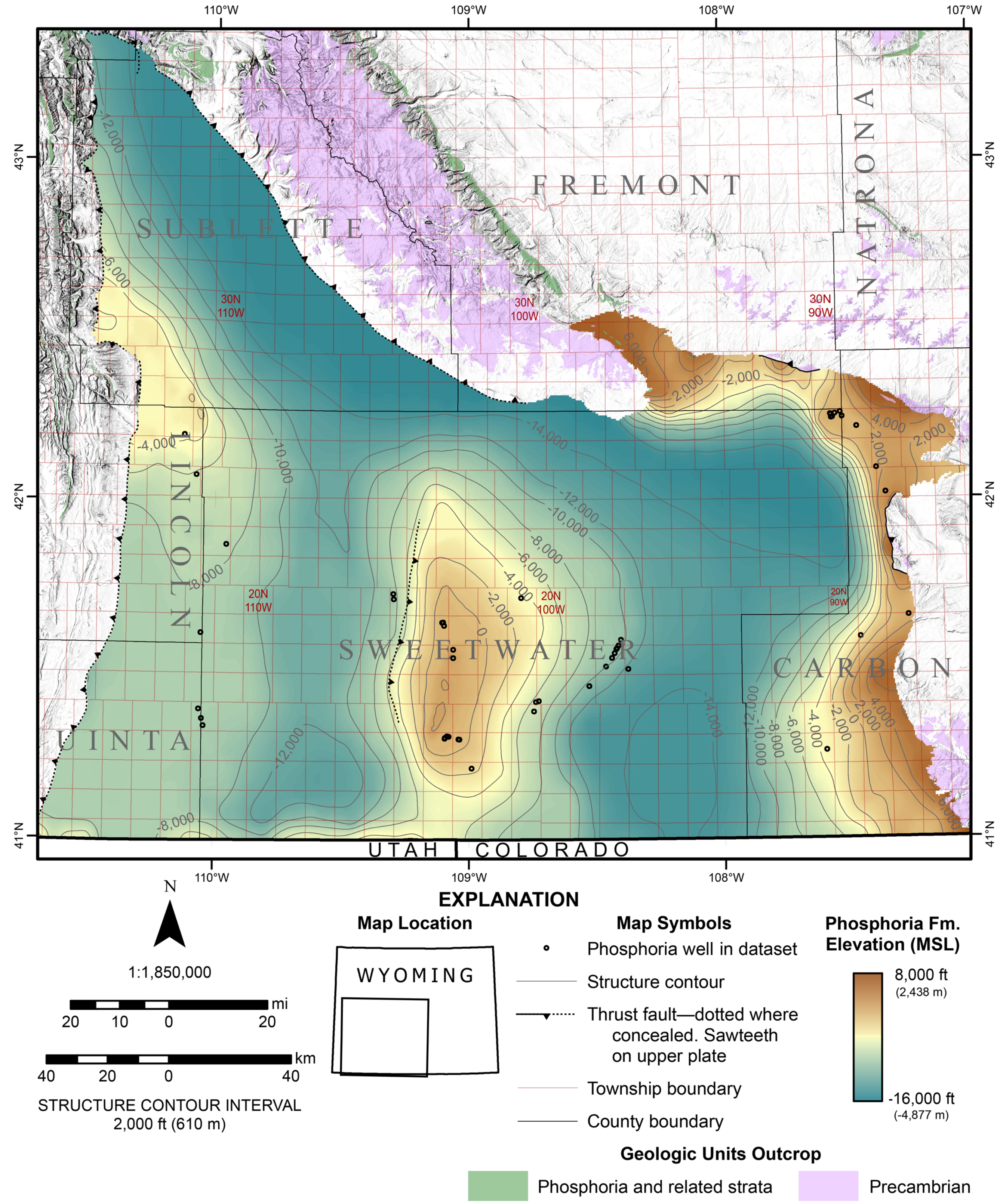

Figure 7. Map showing elevation of the top of the Phosphoria Formation.

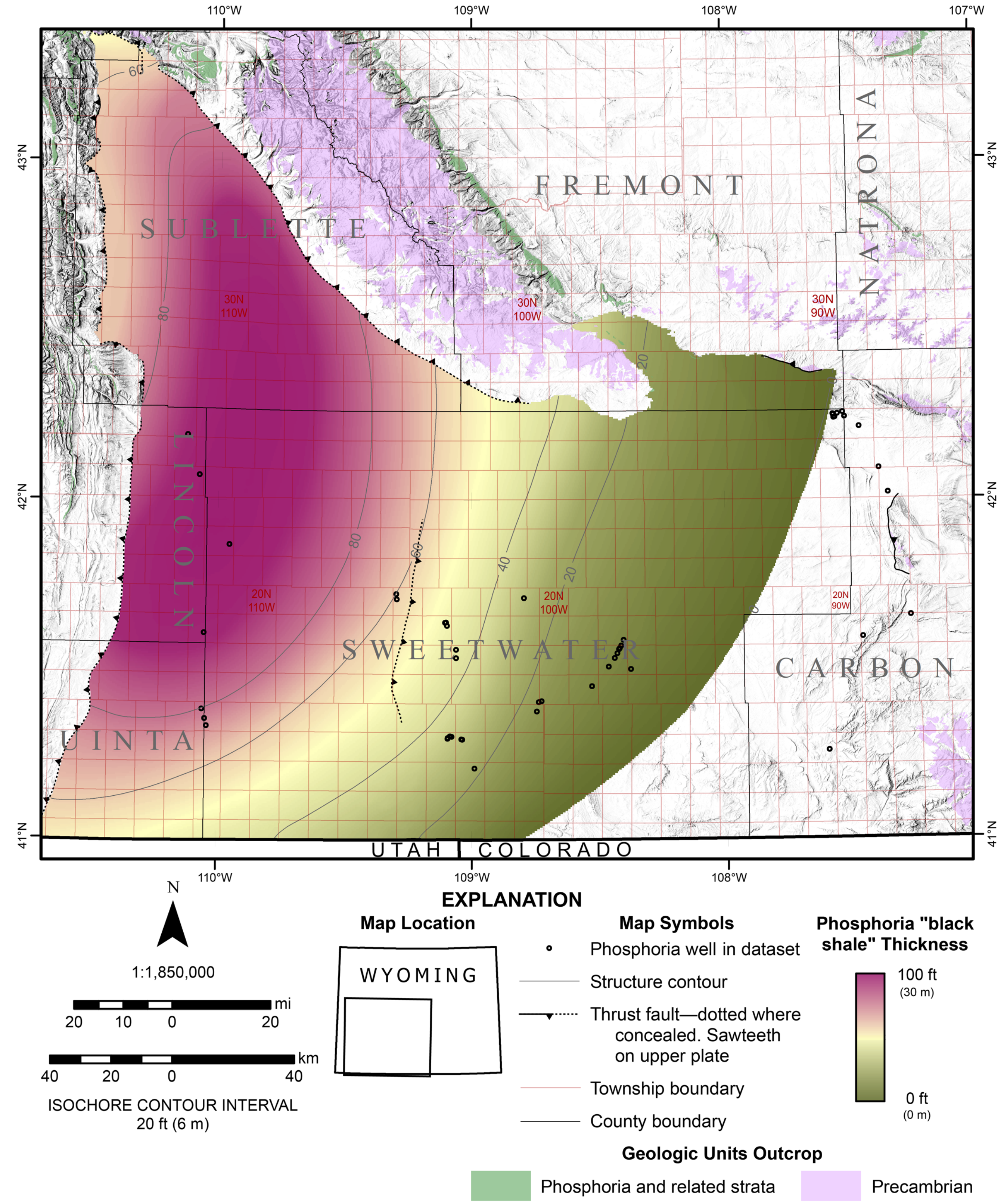

Figure 8. Map showing thickness of the black shale facies of the Phosphoria Formation, after Sheldon (1967).

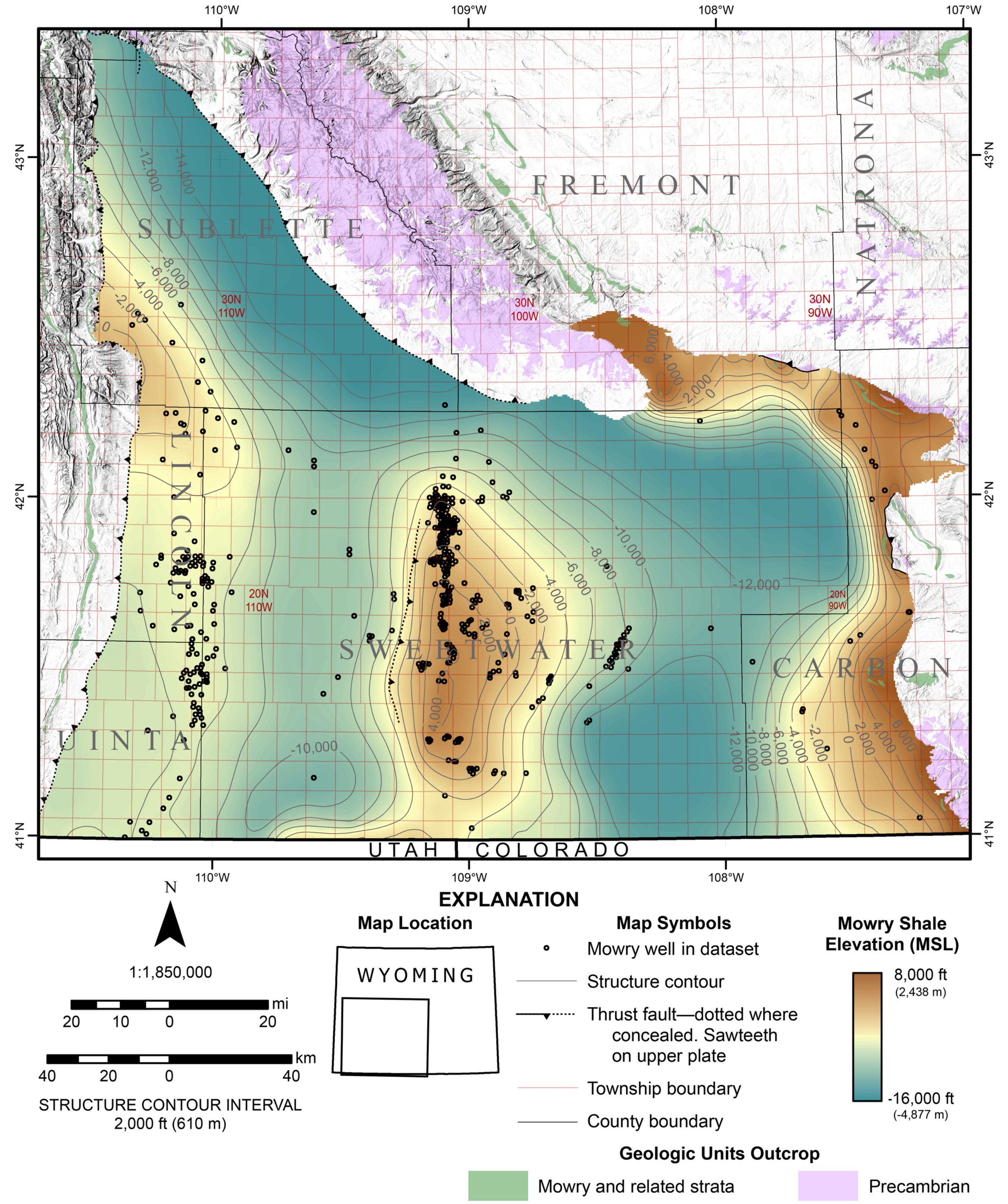

Figure 9. Map showing elevation of the top of the Mowry Shale.

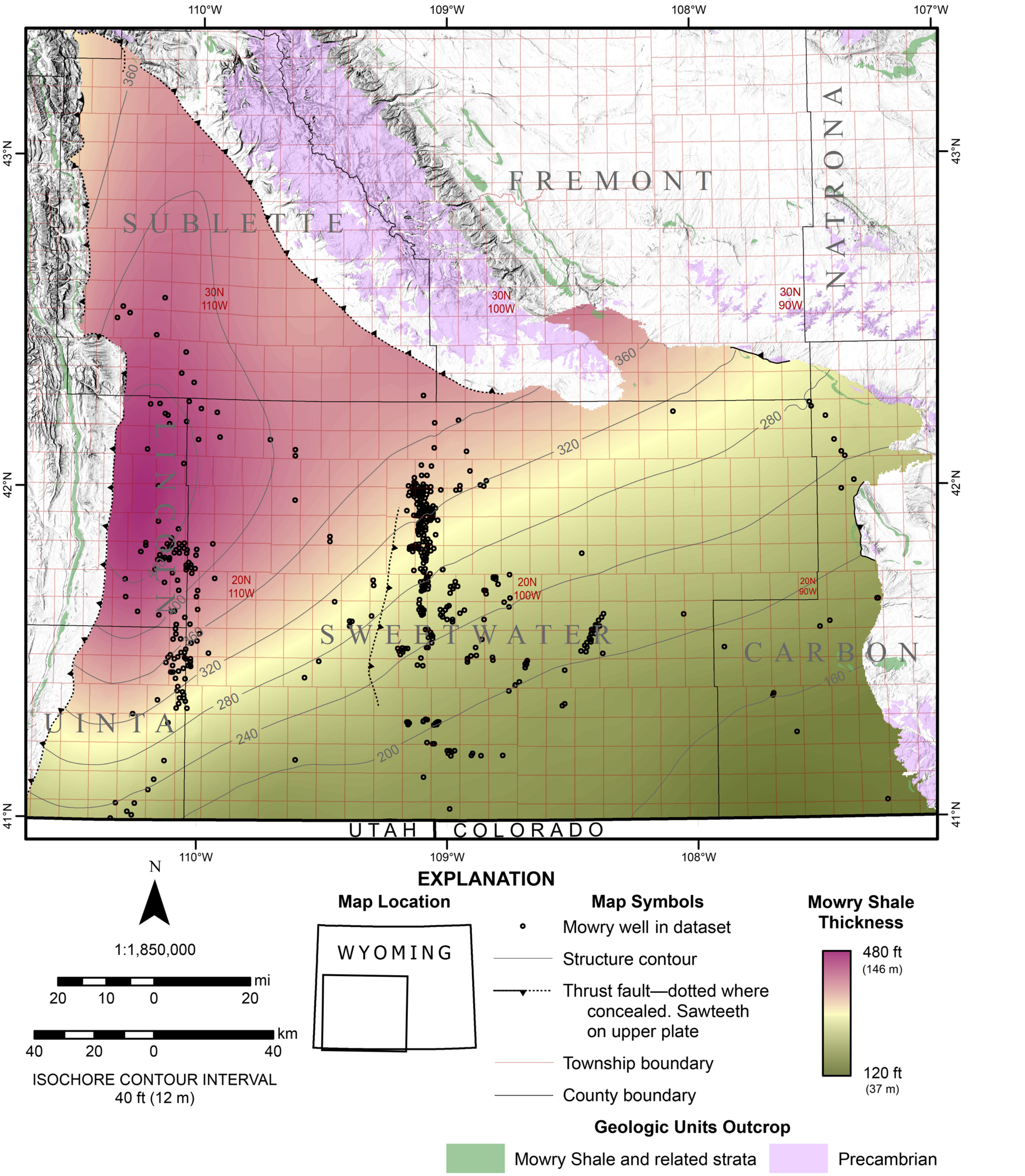

Figure 10. Map showing thickness of the Mowry and Shell Creek shales.

Baxter Shale

The Upper Cretaceous (Coniacian through early Campanian) Baxter Shale and equivalent strata were observed throughout the GGRB. Because of the complex intertonguing relationships between Baxter Shale equivalents and Mesaverde Group sandstones, the contour map of the depth to the top of the Baxter Shale interval (fig. 11) is a time-transgressive surface that represents the depth to the lowermost occurrence of nearshore and coastal sand deposition during the Campanian epoch. Also for this reason, a contour map of the total thickness of the Baxter interval was not generated from this dataset. The top of the Baxter surface (fig. 11) exceeds -3,350 m (-10,991 ft) MSL along the southwestern flank of the Wind River Range, and reaches a depth of approximately 3,050 m (-10,007 ft) in the central Washakie and Great Divide basins. Baxter Shale equivalents are shallowest along the eastern and northern margins of the GGRB, where the Steele Shale crops out at elevations of 1,990 to 2,340 m (6,529 to 7,677 ft) MSL, and in the Rock Springs Uplift, where the Baxter Shale crops out at approximately 2,630 m (8,629 ft) MSL on Aspen Mountain, south of Rock Springs. The top of the Baxter surface shallows to approximately 1,350 m (4,429 ft) MSL on the LaBarge platform.

Niobrara Formation

Observation of the Niobrara Formation was limited to the easternmost GGRB, as it pinches out along a northeast-trending line in the middle of the Great Divide and Washakie basins, west of which Niobrara carbonates and calcareous shales are absent, and the stratigraphically equivalent interval consists primarily of noncalcareous shales of the lower Baxter Shale. The Niobrara structure map shows a near-maximum depth of about -2,500 m (-8,202 ft) MSL in the central Washakie and Great Divide basins (fig. 12); however, this maximum occurs in the vicinity of the formation's pinch out, where data are scarce. Niobrara Formation crops out along the eastern margin of the GGRB, at elevations of approximately 1,990 to 2,440 m (6,529 to 8,005 ft) MSL.

Dellenbach (2016) showed that the total thickness of the Niobrara interval increases westward in the Sand Wash Basin; due to increased siliclastic input from the Sevier orogenic belt, the shales between the Niobrara's carbonate benches thicken. However, in the middle of the basin, these carbonate benches pinch out, and the carbonate content of the intervening shales decreases, such that this thickened interval is no longer considered the Niobrara Formation and instead is part of the Baxter Shale. For this reason, thickness contours for the total Niobrara Formation were not generated from this study's dataset. Although carbonate benches in the Niobrara were not correlated as part of this study, in general, the thickness of the benches, and their carbonate content, decreases westward.

Lewis Shale

The Lewis Shale is present in the eastern GGRB, pinching out in the vicinity of the Rock Springs Uplift. The top of the Lewis Shale (fig. 13) is deepest at about -2,500 m (-8,202 ft) MSL in the central Washakie Basin. It is shallowest along the eastern margin of the GGRB, where it crops out at elevations of 1,980 to 2,300 m (6,496 to 7,546 ft) MSL, and along the flanks of the Rock Springs Uplift, where it crops out at approximately 2,030 to 2,270 m (6,660 to 7,448 ft) MSL. The top of the Lewis Shale shallows to approximately -220 m (-722 ft) MSL at the saddle point across the crest of the Wamsutter arch.

The Lewis Shale has a maximum thickness (fig. 14) of 765 m (2,510 ft) immediately north of and on the Dad arch, along the eastern margin of the Washakie Basin. This thickness includes a maximum of approximately 425 m (1,394 ft) of the Dad Sandstone, which locally divides the Lewis into lower and upper shale members. Away from this depocenter, to the west, north, and south, the Lewis thins, pinching out near the Granite Mountains uplift to the north and along the western and southern flanks of the Rock Springs Uplift in the central GGRB. This thickness pattern is hypothesized to have been influenced by the depositional interplay of the "Red Desert delta" and the westward embayment of the Western Interior Seaway where the Lewis Shale was deposited (Asquith, 1970; Roehler, 1993).

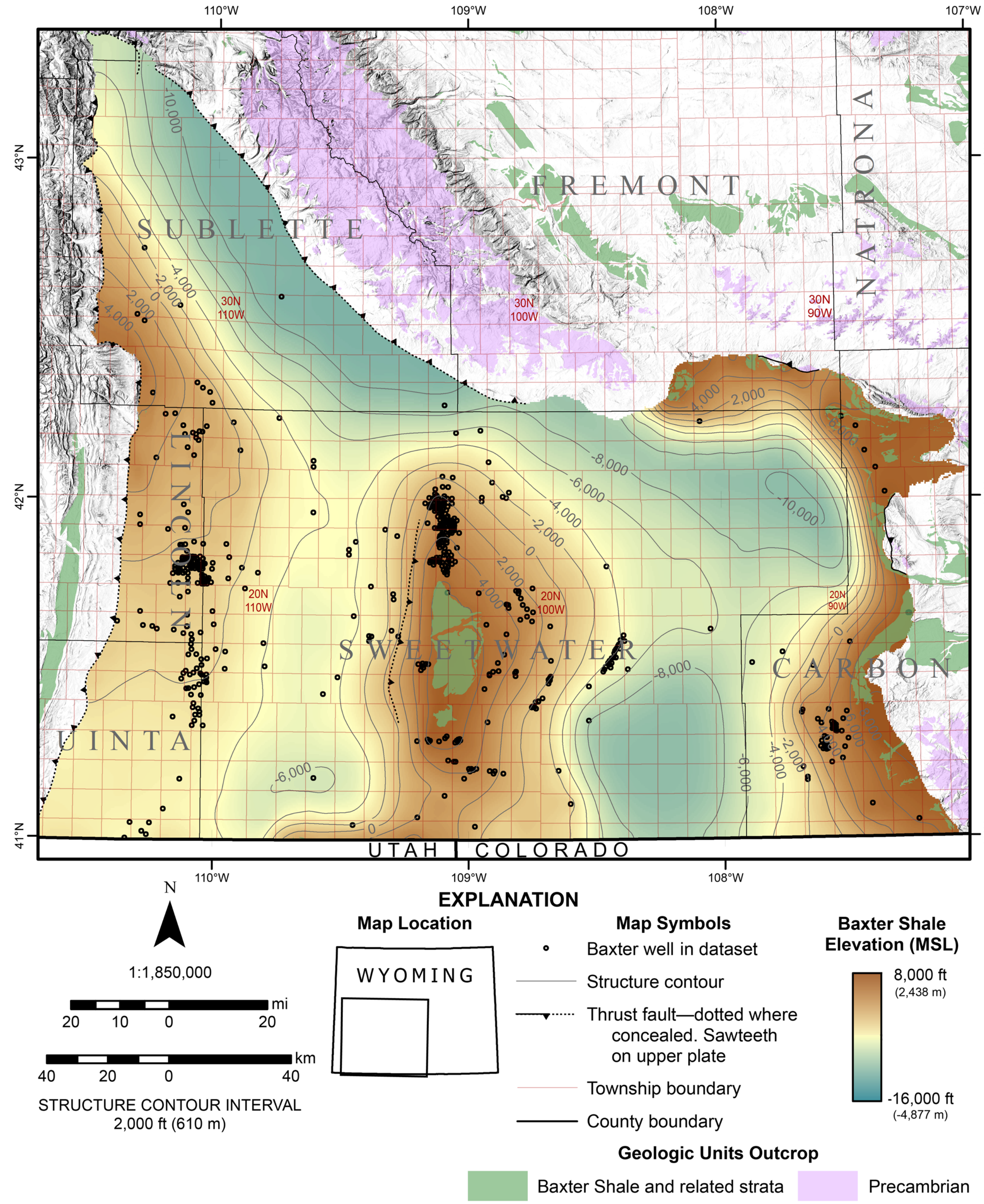

Figure 11. Map showing elevation of the top of the Baxter Shale and related strata.

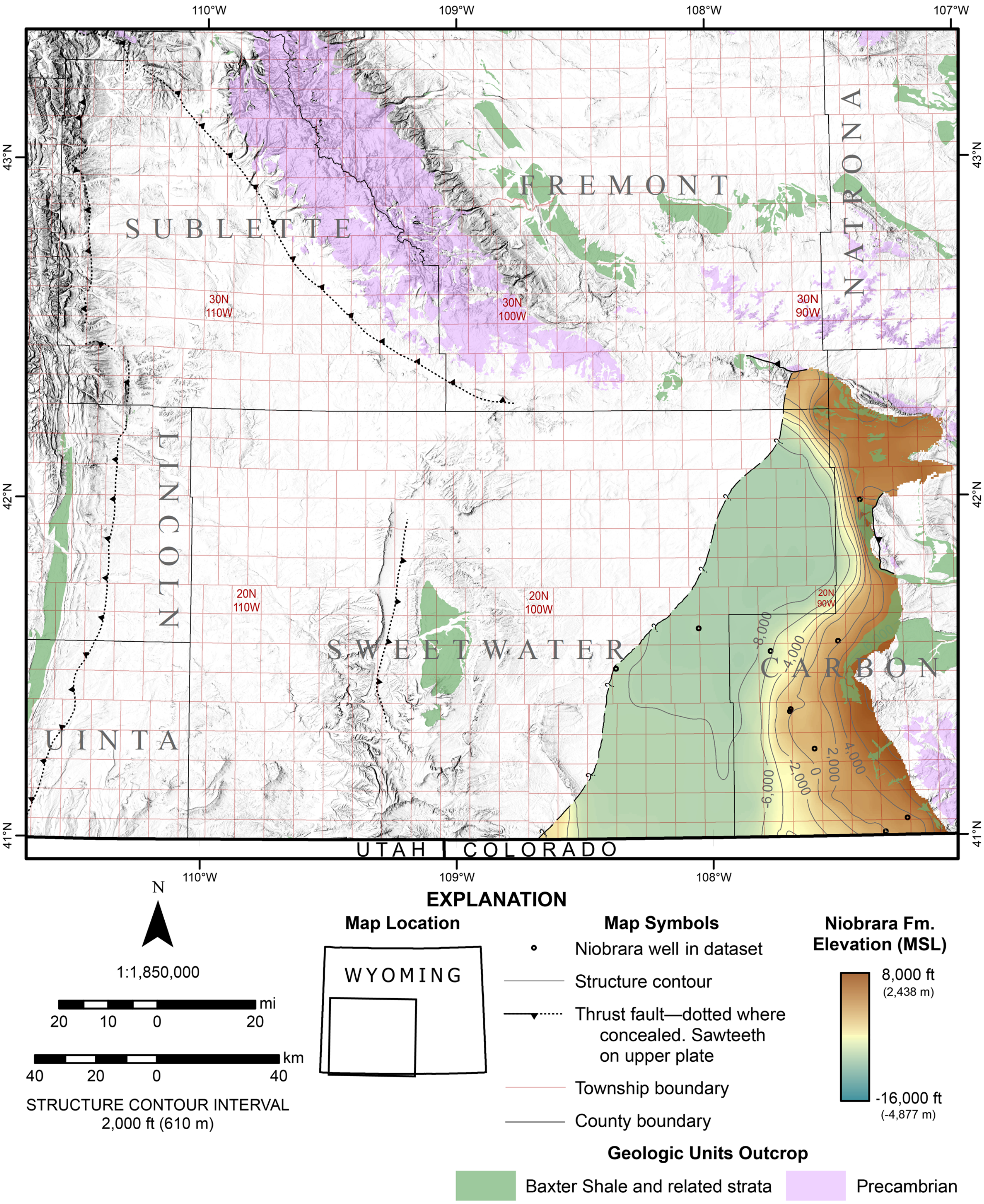

Figure 12. Map showing elevation of the top of the Niobrara Formation. Queried dashed line denotes approximate pinch out.

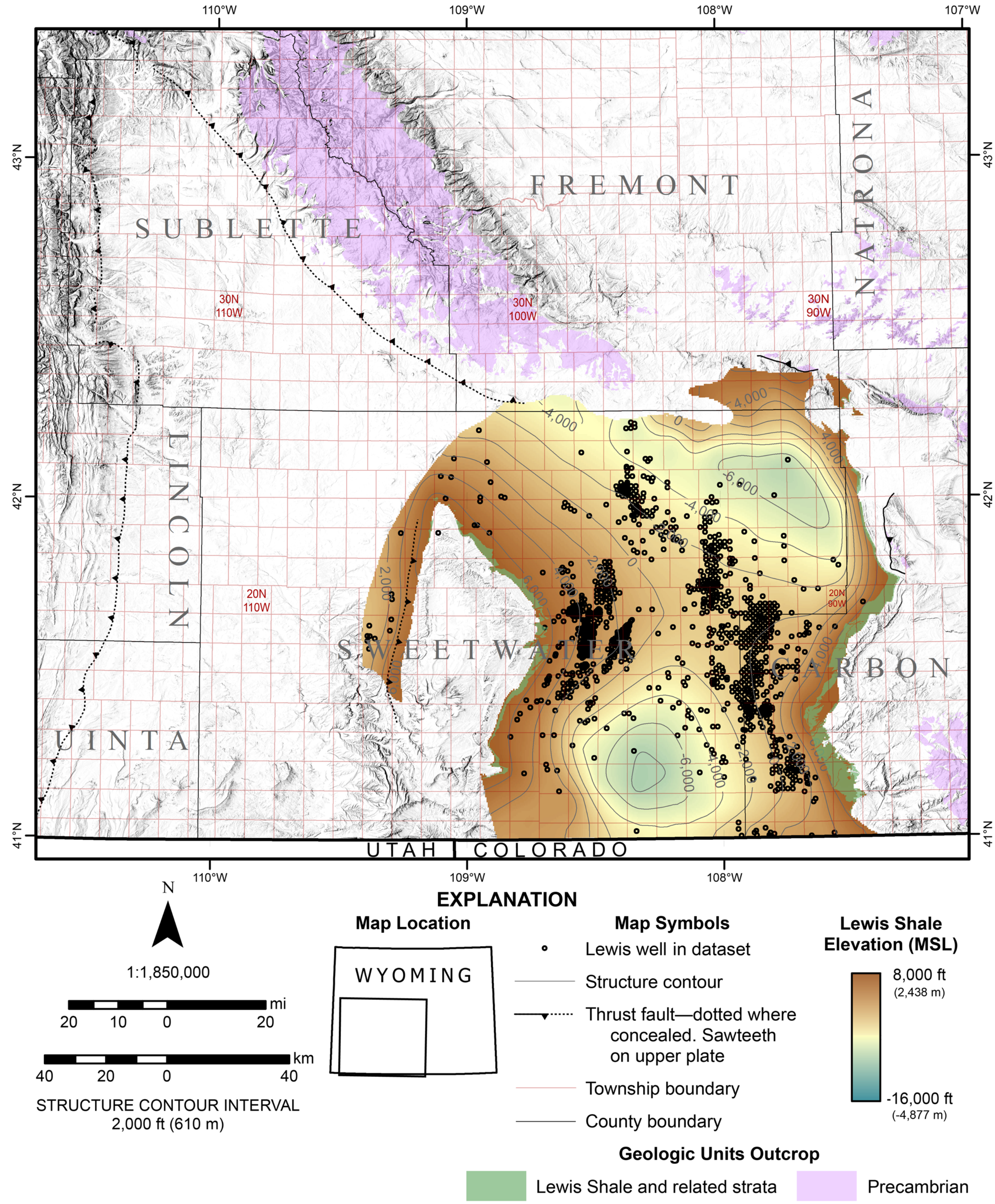

Figure 13. Map showing elevation of the top of the Lewis Shale.

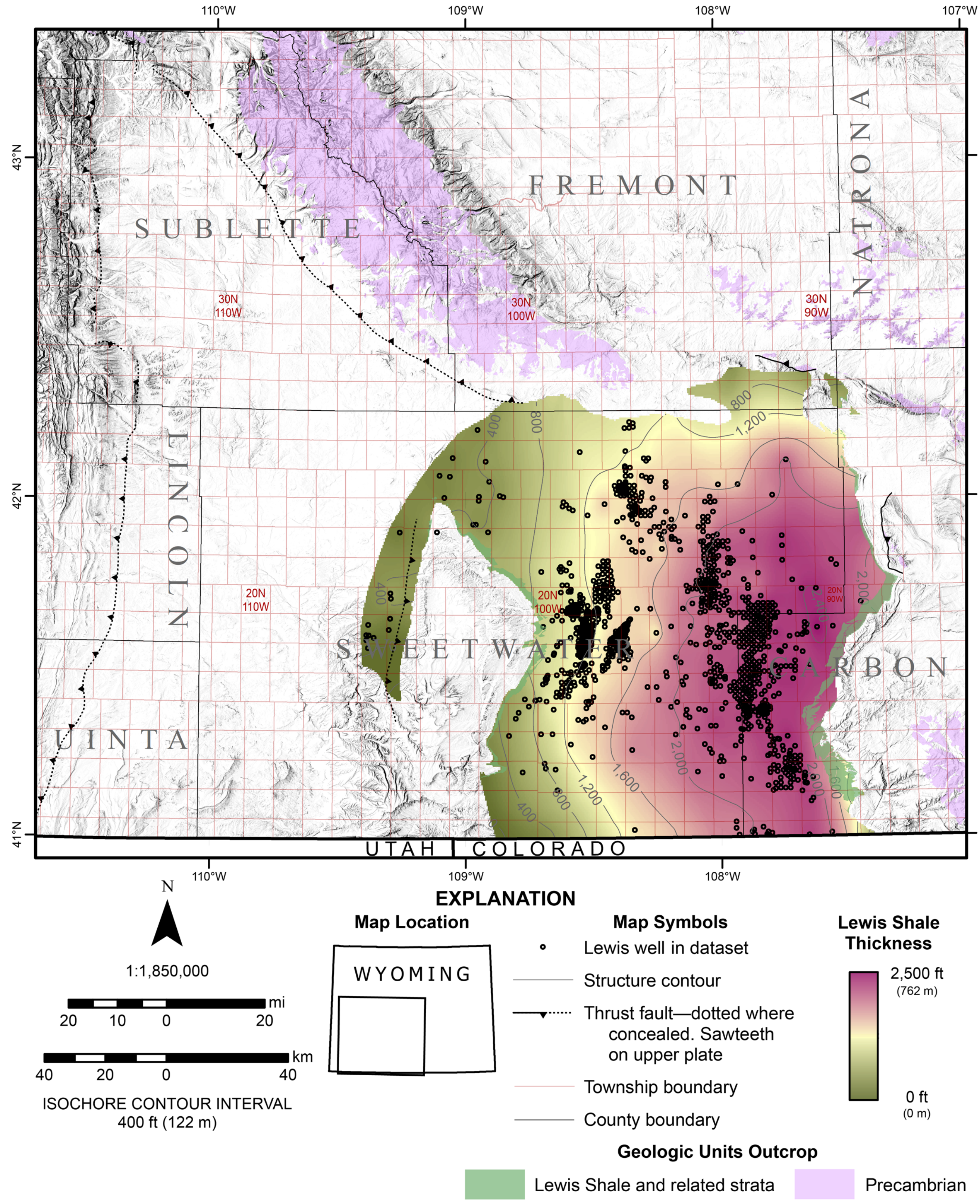

Figure 14. Map showing thickness of the Lewis Shale, including the Dad Sandstone Member.

SUMMARY

To provide a dataset of fundamental subsurface geologic attributes for the GGRB, this study used 2,656 geophysical well logs to correlate key stratigraphic horizons, with a focus on potential continuous oil and gas reservoirs. Contour maps for the potential and emerging continuous reservoirs, which are the Phosphoria Formation, Mowry Shale, Baxter Shale, Niobrara Formation, and Lewis Shale, show how the depth to and thickness of these intervals vary throughout the region.

The database of well-header information, formation tops, downhole temperatures, and structure and thickness contour maps can be accessed online through the WSGS Interactive Oil and Gas Map of Wyoming.

The authors welcome input and discussion on the interpretations of the subsurface stratigraphy, and will continually refine and expand this subsurface database in the GGRB and throughout Wyoming.

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