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Uranium Geology and Resources of the Gas Hills District, Wind River Basin, Central Wyoming

Robert W. Gregory

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Cover photo: Upper part of the Puddle Springs Arkose Member of the Wind River Formation in the high wall of a reclaimed open pit toward the southern end of the Lucky Mc ore deposit trend.

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ABSTRACT

The Gas Hills uranium district is the most productive in Wyoming and one of the most important in the United States. The district, discovered in 1953, produced more than 111 million pounds of uranium concentrate (U_3O_8) between 1954 and 1988 when it ceased production due to declining prices. Production derived from five different mills, three in the Gas Hills, and one each in Riverton and Jeffrey City.

Uranium in the Gas Hills district was mined from roll-front deposits in the Puddle Springs Arkose Member of the Eocene Wind River Formation. The Puddle Springs Arkose Member comprises a vast system of arkosic conglomerates and sandstones derived from erosion of Precambrian rocks in the Granite Mountains, which were uplifted and exposed during the Laramide orogeny. Post deposition, oxygenated, uranium-bearing groundwater flowed northward into the Wind River Basin, promoting mineralization in this complex of very porous and permeable alluvial fans. The resultant uranium roll-fronts form sub-vertical, en echelon stacks concentrated along interfaces in elongate frontal systems or ore trends between alluvial fans. The highest grade uranium ore is generally concentrated in three main ore trends in the west, central, and eastern parts of the district. Estimates indicate a remaining resource of more than 50 million pounds of equivalent uranium oxide concentrate (eU_3O_8).

INTRODUCTION

Background

The nuclear age that began after World War II spurred uranium exploration throughout the western United States. After the discovery of a possible link between uranium deposits and Oligocene tuffaceous sedimentary rocks near the Black Hills of South Dakota (Denson and others, 1951), economic uranium deposits were discovered in several of Wyoming's basins, particularly in the central and northeastern regions of the state (fig. 1). In the Gas Hills, uranium-rich ore was discovered at the surface in 1953 and production commenced in 1954. Uranium production from the Gas Hills district ceased in 1988 due to declining prices, but significant reserves remain.

The Gas Hills district is named for gas seeps from a sequence of Mesozoic-aged rocks exposed in hogbacks that form the flanks of the asymmetric northwest-plunging Dutton Basin Anticline, one of several such Laramide structures situated on the southeastern margin of the Wind River Basin (fig. 2; Soister, 1967b). The Granite Mountains were uplifted during early Eocene time as the trough of the Wind River Basin along its northern margin deepened several thousand feet (Love, 1970). As the newly exposed Precambrian rocks of the Granite Mountains weathered and eroded, a vast system of arkosic conglomeratic fans formed along the flanks of the range. The Wind River Formation was deposited by fluvial systems transporting detritus to the Wind River Basin to the north, while the Battle Spring Formation formed in the Great Divide Basin to the south by similar processes at about the same time. Both the Wind River and Battle Spring formations host economic uranium deposits.

The Puddle Springs Arkose Member in the upper part of the Wind River Formation in the Gas Hills district became the host unit for roll-front deposits as uranium-bearing groundwater percolated through its permeable horizons and encountered reducing environments in the sediments. Roll-fronts are the most common deposit type in the district and are typically separated vertically by impermeable mudstones, siltstones, and shales. Subsequent erosion of the Wind River Formation resulted in the redistribution of uranium within the district and the formation of secondary deposits in addition to the primary roll-fronts.

Mining in the Gas Hills began in 1954 at the Lucky Mc mine and continued until 1987. Three uranium mills in the district, as well as the mills located at Jeffrey City and Riverton, produced uranium concentrate until 1988. Since then, activity has been largely restricted to reclamation of surface pits and mill sites. However, a resurgence in the uranium market beginning in about 2005 resulted in renewed interest in developing remaining economic uranium deposits in the Gas Hills. Wyoming became an "Agreement State" in October 2018, meaning that the Wyoming Department of Environmental Quality (WDEQ) agreed to assume regulatory oversight that was formerly the responsibility of the U.S. Nuclear Regulatory Commission. The end result of becoming an Agreement State is that the permitting and licensure processes should become less tedious and duplicative, shortening the time between discovery and production. Resource evaluation methods vary, but current estimates indicate that more than 50 million pounds of recoverable uranium concentrate remains in the form of reserves or indicated/inferred resources (Nielsen and others, 2013; Beahm, 2017). Future mining will likely involve a combination of conventional and in-situ recovery (ISR) methods.

Scope of report

This publication addresses the geologic factors associated with uranium source rocks, mobilization, mineral precipitation, discovery, and mining history in the Gas Hills district. The information presented here on the uranium geology and resources of the Gas Hills district is intended to aid interested parties in the transition from dormancy to production. Uranium is a critical mineral and thus of great importance to the security of the United States, our nuclear power industry, and also to the economy of

Wyoming. In addition to uranium, rare earth elements (REEs), vanadium, and other critical minerals are also known to occur in roll-front settings. Data compilation and analyses of geologic ore-forming processes are presented in an attempt to inform geoscientists and non-specialists alike on the nature of uranium roll-front deposits.

Geologic setting

Regional geology

The Gas Hills district is situated on the southeastern edge of the Wind River Basin in central Wyoming, approximately 15–20 miles north of the central Granite Mountains (figs. 1 and 2). Other Laramide structures along the margins of the Wind River Basin include the Wind River, Washakie, Owl Creek, and southern Bighorn ranges, and the Casper Arch at its eastern edge. The Wind River Range lies about 70 miles to the west and runs approximately 100 miles northwest to the Washakie Range at the very northwest corner of the basin. East of the Washakie Range are the Owl Creek and southern Bighorn Mountain ranges, which extend another 100 miles east-southeast. At the east margin of the Wind River Basin, between the southern Bighorn Mountains and the eastern end of the Granite Mountains block, is the Casper Arch, an intensely folded, and in some places overturned, anticlinal structure lying at approximately the same elevation as the Wind River Basin.

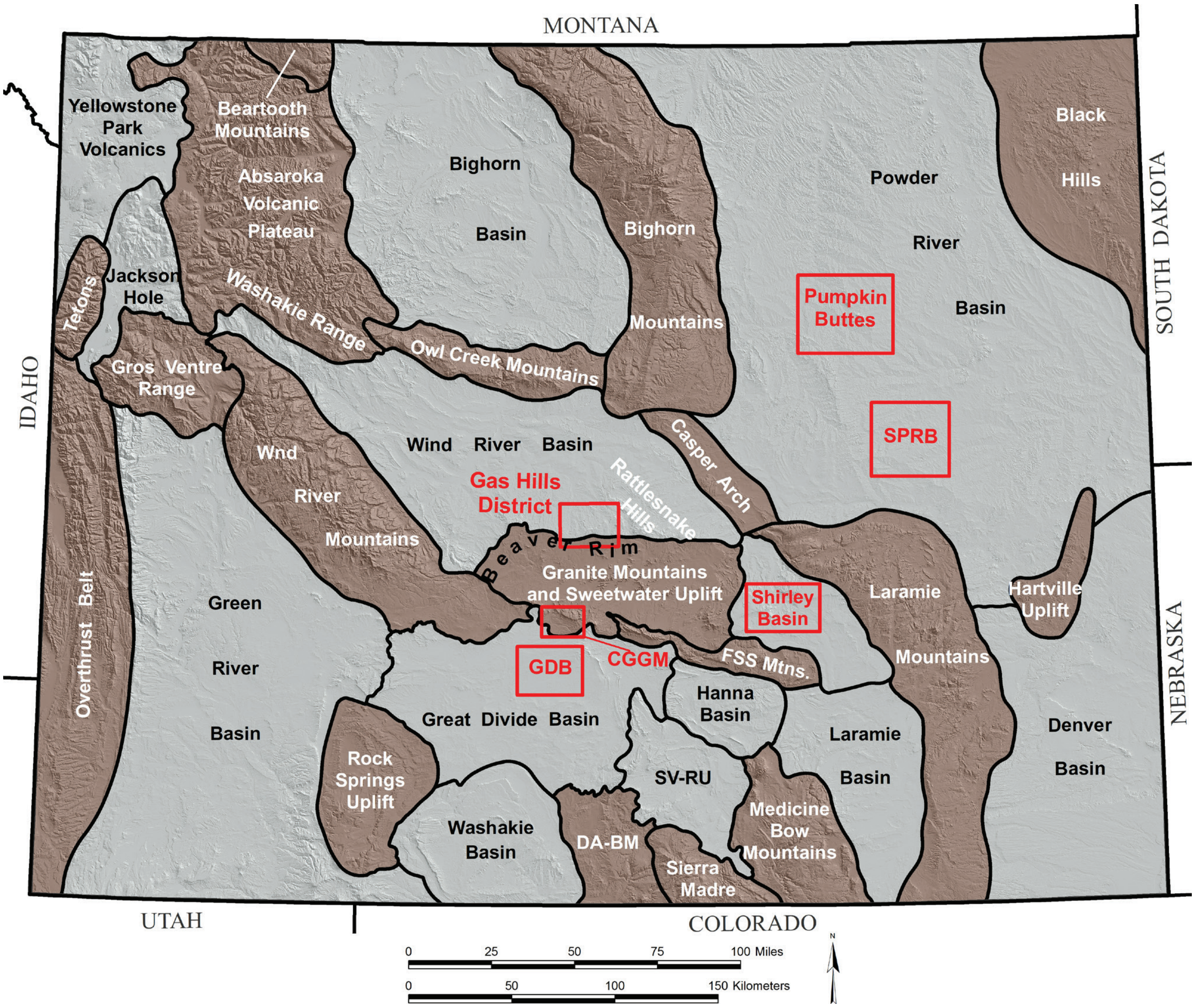

Figure 1. Generalized locations of the Gas Hills and other uranium mining districts (red text and outlines) in the greater central Wyoming uranium province, including Crooks Gap-Green Mountain (CGGM), Great Divide Basin (GDB), Shirley Basin, Pumpkin Buttes, and the southern Powder River Basin (SPRB). Laramide and other structural high provinces are labeled in white text including the Ferris, Seminoe, and Shirley mountains (FSS) and Dad Arch-Battle Mountain areas (DA-BM). Sedimentary provinces and basins are labeled in black text, including the Saratoga Valley-Rawlins Uplift region (SV-RU).

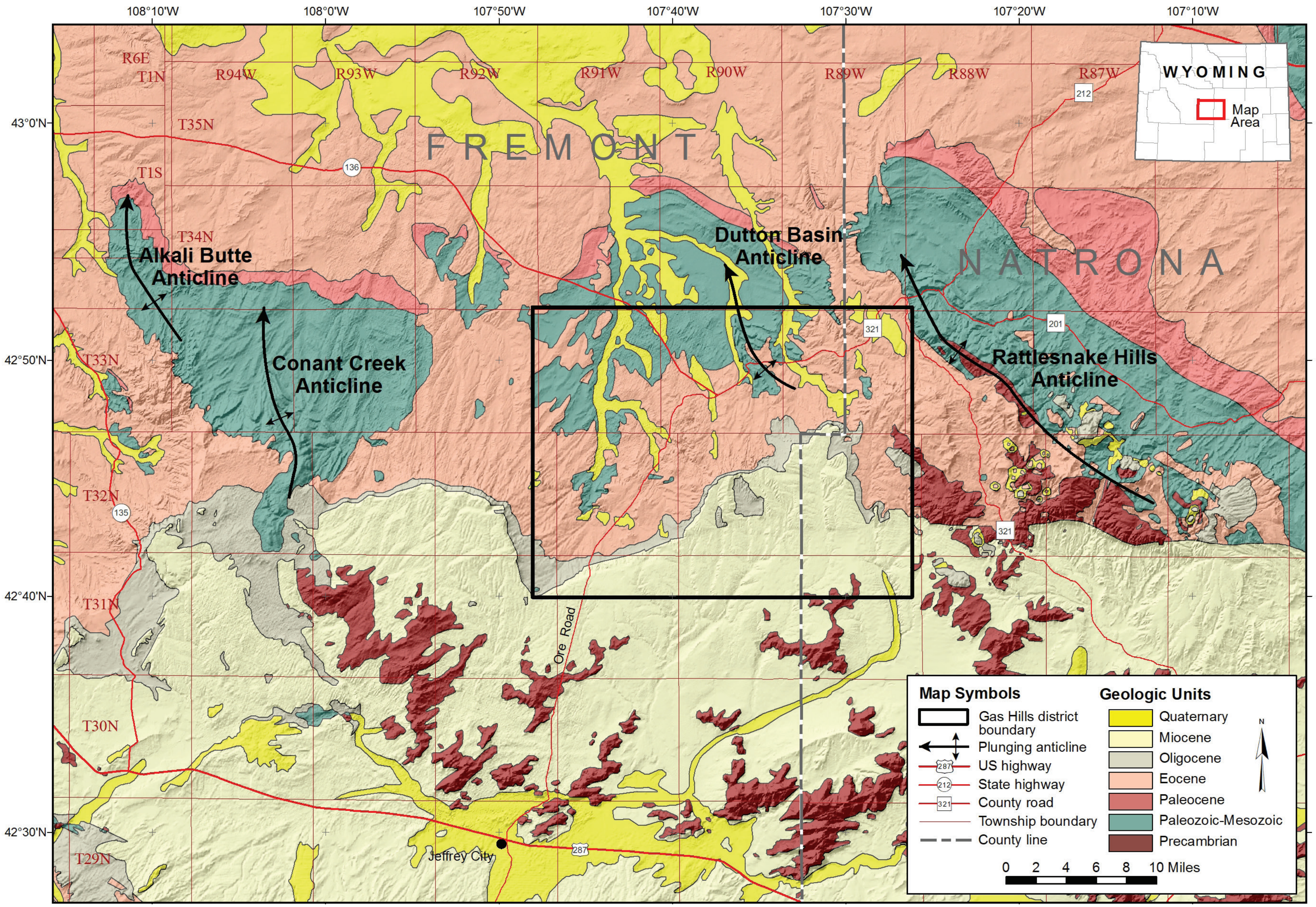

Figure 2. Simplified geologic map of the southeastern portion of the Wind River Basin showing northwest-trending anticlines common in the region. The Gas Hills hogbacks are located in the northeast sections of T. 33 N., R. 90 W., on either side of the Dutton Basin Anticline. Rock units have been grouped by age. Modified from Love and Christiansen (1985).

Wind River Basin

The Wind River Basin is a trapezoidal-shaped structural depression in central Wyoming occupying approximately 8,500 square miles (fig. 1). Laramide compressional forces resulted in a conspicuous northwest trend to numerous features within and around the basin (fig. 2). Pre-Mesozoic and older rocks dip basinward at relatively gentle angles along the south, southwest, and west margins. These rocks dip steeply and are commonly overturned in areas along the north as well as eastern flanks. From the Precambrian cores of the mountain ranges to the basin axis, structural relief is thought to exceed 35,000 ft in places (Love, 1970). Following is a brief summary of a few of the prominent structural features of the Wind River Basin, particularly in the vicinity of the Gas Hills district. For more detailed analyses of the stratigraphy and structure of the Wind River Basin, the reader is referred to the works of Soister (1968) and Keefer (1970), respectively.

Granite Mountains

The Granite Mountains have had a unique geologic history and a profound effect on the Gas Hills uranium mining district. Most of the rocks comprising the Granite Mountains are Archean in age, but include extensive Proterozoic dikes and other mafic intrusive bodies. Volcanism during the middle and late Eocene also intruded the northeastern part of the range near the Rattlesnake Hills (figs. 1 and 2). During the Laramide deformation of the Rocky Mountain region, the Granite Mountains block was thrust generally south-southwestward while the Wind River Basin was subsiding. The range was uplifted several thousand feet from latest Cretaceous through early Eocene time. During the same time frame, approximately 18,000 ft of fluvial and lacustrine sediments accumulated in the Wind River Basin (Keefer, 1970). Laramide deformation also resulted in a series of generally northwest-trending folds along the southeast margin of the Wind River Basin, involving sedimentary units of Cambrian through Cretaceous age; the Dutton Basin Anticline, which forms the hogbacks of the Gas Hills, is one such Laramide structure. The Granite Mountains were extensively eroded during the Eocene and Oligocene, supplying sediment to the Wind River and surrounding basins forming the Wind River Formation (and its time equivalents in other basins), the host for the Gas Hills uranium deposits (Love, 1970).

The Granite Mountains block underwent significant subsidence during the Miocene when as much as 3,000 ft of mostly porous, silty, and clayey sandstone, with some widespread conglomerate beds, was distributed over the region surrounding the Granite Mountains (Love, 1970). During the Pliocene time the Granite Mountains were down-dropped along mostly normal faults of the North and South Granite Mountains fault systems while the rest of the region experienced broad regional uplift. By the end of Pliocene time the Granite Mountains were largely buried by rocks of Miocene and Pliocene age; only the highest peaks of the range are exposed today (Love, 1970).

Northwest-trending anticlines along the southeast margin of the Wind River Basin

Several Laramide-aged, northwest-trending anticlinal structures occur along the southern margin of the Wind River Basin, including the Dutton Basin Anticline in the Gas Hills uranium mining district (fig. 2). Most are northwest-plunging asymmetrical structures and some show axes that veer more northward, such as the Conant Creek and Alkali Butte anticlines. The structures that formed during the Laramide resulted in topography of considerable relief by the time the Wind River Formation began accumulating in the early Eocene. As the anticlinal structures that were exposed at that time began eroding, rocks as young as the Paleocene Fort Union Formation contributed detritus to the Wind River Formation. In the Gas Hills district, the Wind River Formation lies in unconformable contact with rocks as old as the Triassic Chugwater Formation and as young as the Cretaceous Cody Shale, particularly along the Dutton Basin Anticline.

STRATIGRAPHY OF CENOZOIC ROCKS

Eocene

Wind River Formation

The Wind River Formation covers most of the areal surface of the Wind River Basin. Regionally, the formation was deposited on a north-sloping erosional surface between the Granite Mountains to the south and the trough of the Wind River Basin to the north. The erosional surface included the pre-Eocene sedimentary rocks in Laramide structures at the basin margin as well as the newly exposed Precambrian core of the Granite Mountains in the highlands to the south, thus the thickness of the Wind River Formation varies significantly within a short distance from place to place in the Gas Hills area and its base is in contact with a number of different rock formations.

In the Wind River Basin, two members of the Wind River Formation are recognized, known from oldest to youngest as the Lysite and Lost Cabin members (Granger, 1910). Only the Lost Cabin Member is present in the Gas Hills district (fig. 3).

Lost Cabin Member and Central Carbonaceous Zone

Van Houten divided the Lost Cabin Member of the early Eocene Wind River Formation in the Gas Hills district into two units (1954, 1964): from oldest to youngest, the lower fine-grained member and the upper coarse-grained member (Zeller and others, 1956; Soister, 1958; fig. 3). Soister (1958) further divided the upper coarse-grained member into the Puddle Springs Arkose Member and

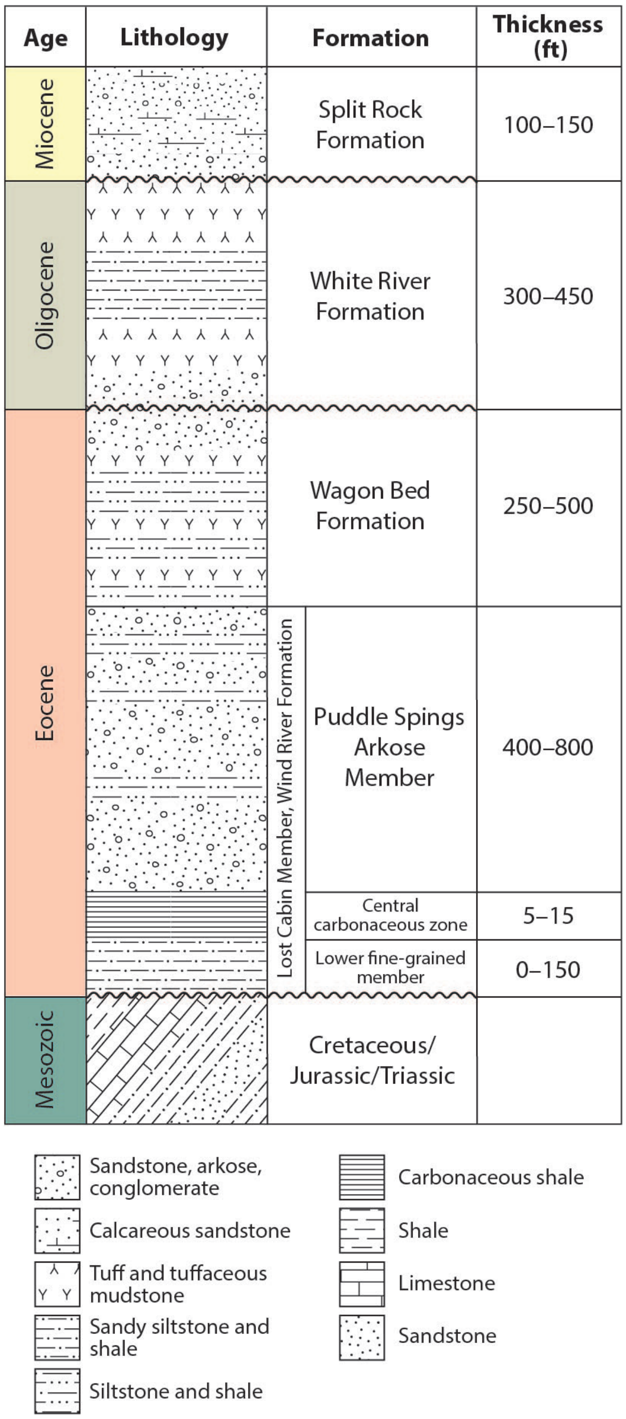

Figure 3. Generalized schematic stratigraphic column of rock units in the Gas Hills district. Time epochs colors match those displayed in figure 2.

the upper transition zone. Love (1970) proposed that the upper transition zone be assigned to the middle Eocene Wagon Bed Formation on the basis of 1) its bentonitic matrix being so similar in character to that in the Wagon Bed Formation, 2) its genetic relationship to the uplift of the Granite Mountains that stripped the Wind River Formation strata from the core of the mountains, and 3) its areal extent being more in agreement with that of the Wagon Bed than of the Wind River Formation. A brief description of this unit is included with that of the Wagon Bed Formation.

Lower Fine-Grained Member

The lower fine-grained member, as described by Soister (1968), is 0–150 ft thick in the Gas Hills district and consists of a thin, discontinuous basal conglomerate with overlying interbeds of siltstone, sandstone, and claystone (fig. 4). Additionally, a discontinuous sequence of carbonaceous shale, claystone, and locally thin lignite and subbituminous coal occurs near the top of the unit.

Siltstone is the primary lithology of the lower fine-grained member. The siltstones are mostly grayish-green, sandy and clayey, and generally range from 1–14 ft thick (Soister, 1968). Sandstones vary in color from light gray to light yellow to olive, very fine to fine grained, are mostly subround-round, well sorted, and consist primarily of reworked material from the Cloverly, Morrison, and Sundance formations as well as the Nugget Sandstone (Soister, 1968). Most sandstones are silty, locally arkosic, and lenticular, ranging in thickness from a few inches to a few feet. Claystones vary in color from olive to grayish green, with some conspicuous thin beds of grayish-red, red, and reddish-brown. Many claystones weather into blocky fragments, while some form bentonitic weathered outcrops. Most claystones are 1–3 ft thick (Soister, 1968).

Of significance to the occurrence of uranium deposits is a 5–15-ft-thick sequence of carbonaceous shale and thin coal beds near the top of the member, which Soister (1968) refers to as the central carbonaceous zone (fig. 3). Soister notes that the coal beds are up to 1.2 ft thick. The carbonaceous layers range from a few inches to about 38 ft in thickness (Soister, 1968), some of which are traceable for several thousand feet, while others are more localized, either due to pinch-out or truncation by cut-and-fill. Some carbonaceous layers are known to interfinger with beds of the lower Puddle Springs Arkose Member.

Puddle Springs Arkose Member

The lower fine-grained member, and central carbonaceous zone where present, grade upward into the Puddle Springs Arkose Member, the only rock unit in the district that hosts economic uranium deposits. The Puddle Springs (Soister, 1966c) Arkose Member is a

Figure 4. Subtle outcrops of the lower fine-grained member of the early Eocene Wind River Formation near Sarcophagus Butte. View is looking northeast toward the Gas Hills hogbacks.

400–800-ft-thick sequence of massive, coarse- to very coarse-grained conglomeratic arkose and arkosic sandstone with lesser amounts of fine- to medium-grained sandstone and feldspathic arkose (Soister, 1968). Interbedded with the arkosic beds are lesser amounts of siltstone, claystone, and shale that is variably carbonaceous, particularly at its base (figs. 5 and 6).

The Puddle Springs Arkose Member comprises almost all of the Wind River Formation outcrops in the Gas Hills district, with its main surface exposures in the low foothills north of Beaver Rim. Some horizons are unconsolidated while others are cemented with clay, calcite, ferric oxides, dark manganese oxides, and other minerals such as gypsum, jarosite, pyrite, silica, and oxides of arsenic, molybdenum, and uranium (Soister, 1968). Other cementing minerals include iron oxides, hydroxides, sulfides, sulfates such as gypsum and jarosite, and locally silica (Soister, 1968).

Figure 5. Upper part of the Puddle Springs Arkose Member of the Wind River Formation in the high wall of a reclaimed open pit toward the southern end of the Lucky Mc ore deposit trend.

In general, this unit is massive and lacks bedforms other than some localized fluvial crossbeds in medium- to fine-grained sandstone. The rocks that make up the Puddle Springs Arkose Member are primarily derived from the Granite Mountains to the south, with minor

Figure 6. Oxidized sandstone and arkose of Puddle Springs Arkose Member in normal faulted contact with beds of the central carbonaceous zone of the Wind River Formation near George Ver and Frazier-Lamac historic pits on the northern portion of Lucky Mc ore deposit trend.

input from various pre-Cenozoic rocks including siliceous detritus from the Mowry Shale and chert pebbles from the Cloverly Formation eroded from the Dutton Basin Anticline (Soister, 1968). The thickness of the Puddle Springs Arkose Member ranges from zero, where it pinches out at its margins, to about 800 ft, but averages 400–800 ft (Soister, 1966c).

Pebble-cobble-boulder conglomerates

In addition to the massive arkose, the Puddle Springs Arkose Member contains numerous granite pebble, cobble, and boulder conglomerate beds, chiefly in the eastern and western areas of the district. These conglomerate beds all exhibit increases in both thickness and coarseness southward toward the Granite Mountains. Soister (1968) named the three most distinct of these, from oldest to youngest, the East Canyon Conglomerate, the Dry Coyote Conglomerate, and the Muskrat Conglomerate beds. Soister (1967a, b) mapped the outcrops of the Dry Coyote and the stratigraphically higher Muskrat conglomerates, which occur in the western portion of the Gas Hills district. The stratigraphic position of the East Canyon Conglomerate is less certain; it overlies pre-Cenozoic rocks in places and is also interbedded with medium- to coarse-grained arkosic beds of the Puddle Springs Arkose Member (fig. 7).

The Dry Coyote and Muskrat conglomerate beds are relatively thin, averaging 10–30 ft and 10–20 ft in thickness, respectively, and extend areally for several miles to the west and north from the western part of the Gas Hills district (fig. 8). The East Canyon Conglomerate in the eastern portion of the district is a thicker and relatively narrow channel deposit about 2–4 miles wide and more than 15 miles long, north to south, ranging in thickness from 200–300 ft, but approaches 700 ft thick in some drill holes (Soister, 1968).

Figure 7. Interbedded cobbles of the upper East Canyon Conglomerate and coarse arkosic sandstone of the Puddle Springs Arkose Member, along East Canyon Creek in Sec. 9, T. 33 N., R 89 W., eastern Gas Hills.

Boulders and cobbles in the three conglomerates are primarily granite, granite gneiss, pegmatitic granite, quartz, and quartzite, with lesser amounts of schist, mafic dike material, along with Paleozoic carbonates, sandstones, and conglomerate pebbles from the Cambrian Flathead Sandstone (see Soister, 1968 for more detailed descriptions of this member). The Dry Coyote Conglomerate commonly contains uranium minerals such as phsohuranylite, allophane, meta-autunite, and tyuyamunite associated with local carbonaceous sediments interbedded with the conglomeratic layers (Soister, 1968).

The Puddle Springs Arkose Member represents rocks deposited by and in close association with stream channel deposits in an alluvial fan system that formed between the north slope of the Granite Mountains and the Wind River Basin during early Eocene time. The Granite Mountains were uplifted several thousand feet between the late Cretaceous and early Eocene time, as the basin contemporaneously subsided. Along with the stripping of Precambrian material, anticlinal structures formed during the Laramide were also being incised and eroded by these high energy stream systems, supplying Paleozoic and Mesozoic detritus to the fan system.

Some of the more vigorous streams transporting very coarse material deposited granitic boulders up to several feet in diameter, as found in the lower parts of the East Canyon Conglomerate in the eastern Gas Hills district (Soister, 1968). These high energy streams cut canyons through tilted Mesozoic rocks in structures such as the Dutton Basin Anticline, the western flanks of the Rattlesnake Hills Anticline, and other structures exposed during the early Eocene.

As streams approached the basin and decreased their gradient, the coarser material was dropped, while progressively finer-grained sediments were deposited basinward, interfingering with and scouring the lower fine-grained member of the Wind River Formation, as seen locally by discontinuous interbeds and cut-and-fill features (Snow, 1971). Finer-grained sediments interbedded with the arkoses and conglomerates of the Puddle Springs Arkose Member include siltstones and claystones, which most likely accumulated in small ponds and lakes proximal to the main stream channels. Additionally, Soister (1966c; 1968) notes local swamp-like deposits of carbonaceous shale, clay, and thin coal beds in the lower part of the Puddle Springs Arkose Member along the western flanks of Dutton Basin Anticline, which likely protected them from more extensive erosion by the prevailing streams.

Wagon Bed Formation

The Wagon Bed Formation represents rocks of middle and upper Eocene age. This formation was named by Van Houten (1964) based on exposures near Wagon Bed Spring, the type section, below Beaver Rim along its western edge (fig. 1). A gradational contact exists between the top of the Puddle Springs Arkose Member and the overlying Wagon Bed Formation (fig. 3), commonly referred to as the upper transition zone (Van Houten, 1954; Soister, 1968). As previously mentioned, this zone was originally considered part of the Wind River Formation (Soister, 1968) but has subsequently been assigned to the Wagon Bed Formation (Love, 1970). This zone varies in thickness up to 100 ft in the Gas Hills district and is difficult to positively identify in the field due in part to its sporadic occurrence as well as its lithological similarities to both the Puddle Springs Arkose Member and the overlying lower part of the Wagon Bed Formation (Soister, 1968). This zone contains numerous tuffaceous and bentonitic mudstone layers, similar to those in the Wagon Bed Formation (Soister, 1968). This sequence generally consists of very coarse to coarse-grained, grayish-yellow-green to pale-olive, medium- to fine-grained arkose and arkosic sandstone with similarly colored interbedded shale and minor tuffaceous mudstone (Soister, 1968; Armstrong, 1970).

Figure 8. Sandstone, arkose, and coarse conglomerate of the Muskrat Conglomerate in the Puddle Springs Arkose Member, Sec. 31, T. 33 N., R. 90 W., (about 1.5 miles south-southeast of the location of Puddle Springs).

There are six additional units mapped by Van Houten (1955) in the Gas Hills area. Below is a very general description of the formation, and the reader is referred to Van Houten (1955, 1964) for more detailed descriptions of those individual units with respect to their location along the Beaver Rim escarpment.

Most of the units within the Wagon Bed Formation mapped by Van Houten (1955) include prominent resistant cliff-forming beds of tuffaceous siltstone and mudstone interbedded with mostly softer, unconsolidated, locally bentonitic or sandy siltstone, mudstone, and local coarse conglomerates (fig. 9). The resistant ledges are generally light olive to light green and light gray in color, locally exhibit a nodular surface texture with vuggy porosity, and are interbedded with softer mudstones and arkoses of similar color. Those in the lower units commonly display a reddish to yellowish secondary staining not typically seen in similar beds higher in the formation. Also interbedded throughout most units are local vitric and lapilli tuffs and thin, poorly consolidated and poorly sorted conglomerate layers. Some of these conglomerate layers contain boulders up to 6 ft in diameter, mostly in the eastern outcrops north of Beaver Rim; boulders generally decrease in size farther west along the escarpment. Conglomerate beds in the lower part of the formation are predominantly composed of Precambrian granitic and gneissic boulders and cobbles, whereas those higher in the Wagon Bed Formation, particularly in the upper two units (Van Houten, 1964), are dominated by andesitic material derived from the Rattlesnake Hills volcanic field.

The Wagon Bed Formation is generally between 250–400 ft thick in the Gas Hills district, thickening eastward to well above 500 ft. The disconformity between its top and the overlying Oligocene White River Formation results in considerable variation in overall thickness. Van Houten (1964) reports a maximum of 550 ft at the east end of Beaver Rim, while Lynds and others (2016) mapped a maximum thickness of 400 ft northeast of the Gas Hills district. Erosion prior to deposition of the White River Formation has removed much of the upper parts of the Wagon Bed Formation in this area (Van Houten, 1964).

The Wagon Bed Formation is exposed in distinctive badland topography in the foothills of most of Beaver Rim. Toward the base of the formation there is abundant debris derived from the continued erosion of the Precambrian Granite Mountains core, the abundance of which decreases progressively up section. Volcanism from the Rattlesnake Hills intrusives supplied pyroclastics and coarse detritus derived from extruded andesite, phonolite, trachyte, and dacite, primarily as pebbles, cobbles, and boulders in conglomeratic layers in the formation (Van Houten, 1964). The abundance and coarseness of these layers generally decreases with distance from the Rattlesnake Hills volcanic field. The volcanic detritus in the older units of the Wagon Bed Formation are generally sodic trachyte, while those in the younger units are more alkalic andesite (Van Houten, 1964). There are localized accumulations of volcanic debris derived from the Absaroka volcanic field (Van Houten, 1964) at the west end of Beaver Rim.

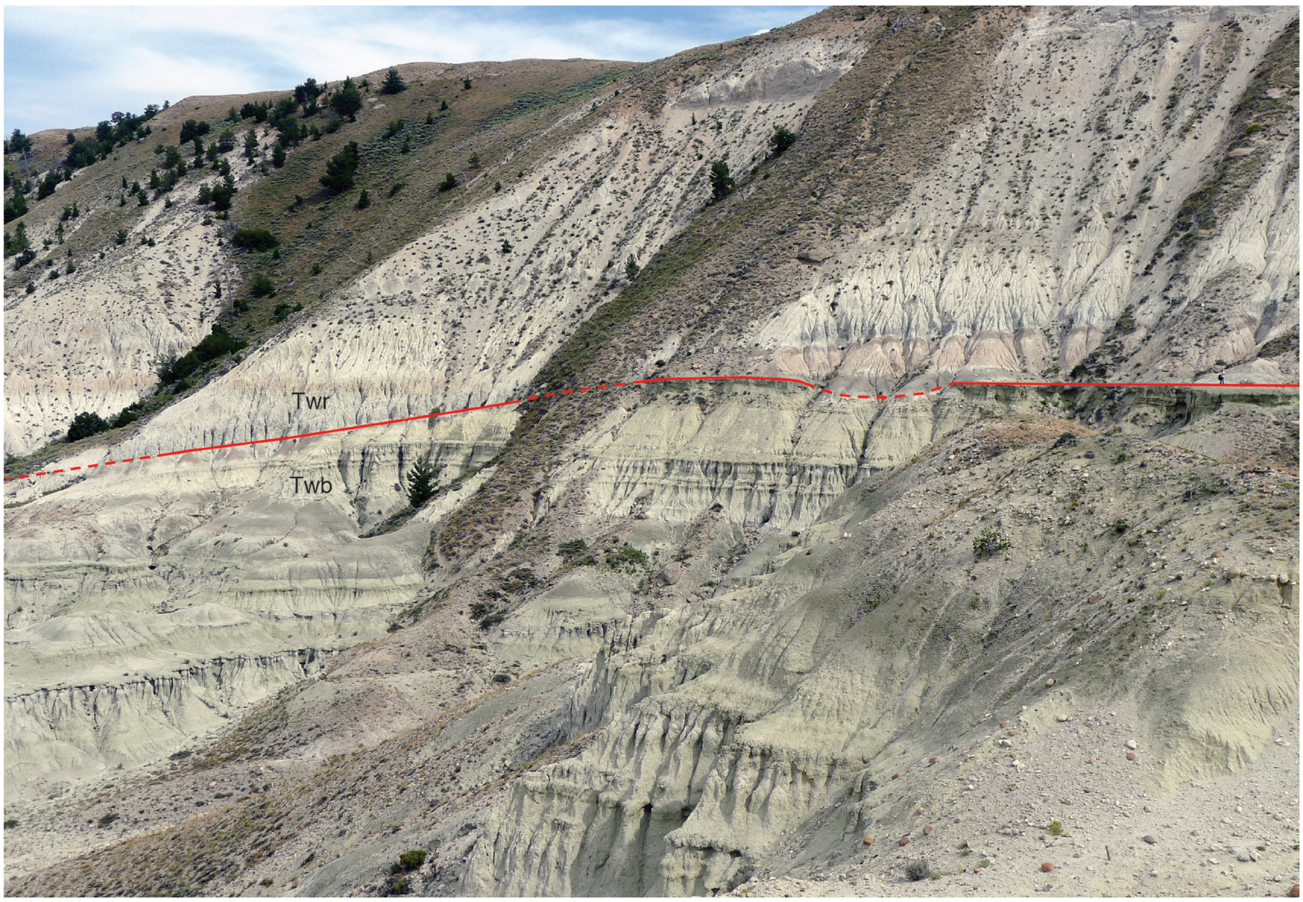

Figure 9. The Oligocene White River Formation (Twr) unconformably overlies the light greenish-tinted badlands topography of the Wagon Bed Formation (Twb) near the base of Beaver Rim.

Oligocene

White River Formation

Significant amounts of the Wagon Bed Formation and locally parts of the upper Wind River Formation were eroded prior to deposition of the Oligocene White River Formation (fig. 9), resulting in less predictable location of its contact with the Eocene rocks and significant variations in thickness from place to place, sometimes over relatively short distances. Van Houten (1955) notes that at least 250 ft of upper Eocene strata were removed prior to White River Formation deposition in parts of the greater Gas Hills district. The Rattlesnake Hills volcanoes had ceased activity during the Oligocene, and thus the volcanic material in the White River Formation is a combination of reworked Eocene debris and pyroclastic material from more distant volcanic centers, largely to the west.

The White River Formation in the Gas Hills district consists of up to 300–450 ft of interbedded biotitic vitric tuff, tuffaceous sandstone and mudstone, sandy mudstone, thin beds of pumicite, and scattered thin lenticular conglomerates. The lower part (roughly the lower 50–75 ft) of the formation is primarily white to light gray in color, whereas the upper part shows a yellowish- to orangish-gray hue. Most outcrops are calcareous.

Miocene

Split Rock Formation

The Miocene Split Rock Formation caps most of Beaver Rim, south of the Gas Hills district (fig. 10). This rock unit, as well as the Paleogene section below it, once covered the Gas Hills region entirely, but the present erosion pattern has stripped them back to the Beaver Rim escarpment.

The ledge-forming base of the Split Rock Formation is a poorly sorted, well-rounded, coarse- to very coarse grained conglomerate with a fine- to medium-grained sandstone and arkosic sandstone matrix. Boulders in the basal conglomerate are typically less than one foot in diameter, but are 2–4 ft across locally. This conglomerate varies in thickness up to 30 ft. Large blocks of this conglomerate are commonly scattered along the slope of the escarpment. The formation above the basal conglomerate takes on a relatively homogeneous character of light-gray to brownish-tan, massive to cross-bedded, well-sorted, fine-grained tuffaceous sandstone. The Split Rock Formation also contains conspicuous well-rounded and frosted quartz grains and chert nodules. The overall thickness of the Split Rock Formation in the Gas Hills district is about 150 ft (fig. 10).

Moonstone Formation

The Moonstone Formation is not present in the Gas Hills district but may have some relevance to the uranium deposits there (Love, 1970). The erosional remnant of this unit unconformably overlies the Split Rock Formation and laps onto the Precambrian core of the Granite Mountains (fig. 11) approximately 15–20 miles southeast of the Gas Hills district. Its maximum thickness was measured by Love (1961) at 1,356 ft in a measured section composed of 46 separate units of highly tuffaceous, mostly lacustrine sediments, including sandstones, claystones, and shales, many of which contain uranium and thorium.

Figure 10. Interbedded sandstone and conglomerate layers near the base of the Miocene Split Rock Formation at the crest of Beaver Rim.

URANIUM DEPOSITS IN THE GAS HILLS DISTRICT

Host rocks

The uranium deposits in the Gas Hills district are restricted to the Puddle Springs Arkose Member of the Wind River Formation. The lower fine-grained member is largely barren of uranium deposits except for the carbonaceous sediments at its contact with the Puddle Springs Arkose Member (Soister, 1968). The most significant ore deposits in the district were found within coarse fluvial sandstones and conglomerates, mostly in the lower half of the Puddle Springs Arkose Member, which were deposited in a generally north-directed alluvial fan system (Zeller, 1957). The vast majority of uranium deposits in the Gas Hills district occur in the Coyote Creek and Canyon Creek fans (fig. 12). This coarse-grained material is limited to the central parts of the district (Soister, 1968), restricting the east–west extent of mineralization. The Puddle Springs Arkose Member grades into fine-grained, less permeable rocks to the east and west of the main ore deposits. In the vertical plane, ore zones occur over an interval of roughly 250–300 ft (Anderson, 1969), and ore is known to be present up to 700 ft below the surface (King and others, 1965). The orientations of the roll-fronts in the Gas Hills district indicate that the mineralizing fluids migrated from the south to the north. These solution fronts moved within three trends:

Figure 11. Miocene Moonstone Formation seen immediately west of Lone Mountain (center), which is located in secs. 15, 16, T. 30 N., R. 89 W., Natrona County, Wyoming. View is to the northeast, approximately along strike. Light-colored tuffaceous outcrops and overlying porous layers (supporting evergreen tree growth at center) are dipping between 2–3 degrees southeast.

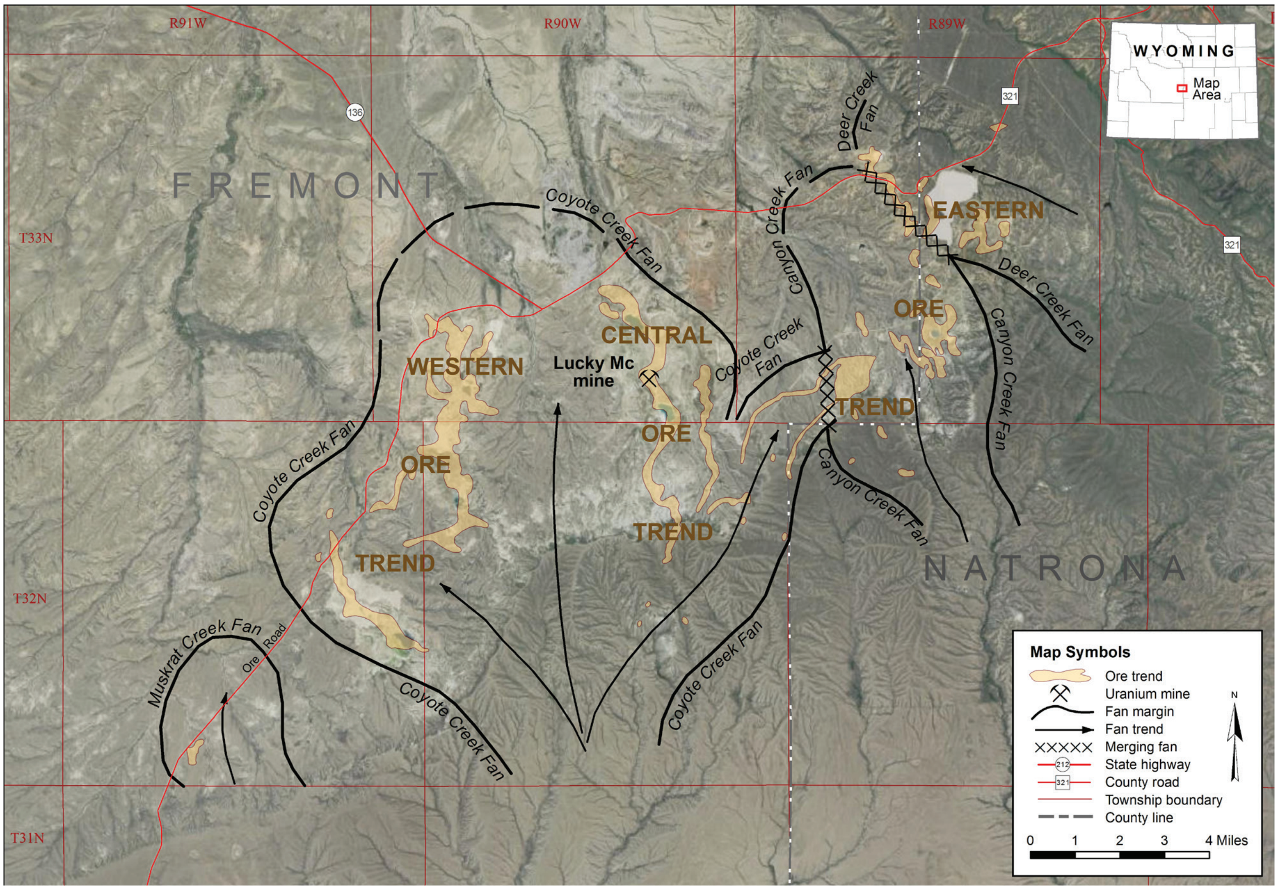

Figure 12. Approximate locations of alluvial fan systems formed during Eocene deposition of the Puddle Springs Arkose Member and their spatial relationship to the western, central, and eastern ore trends. Modified from Power Resources Inc., (1996).

the western, central, and eastern ore Gas Hills trends (fig. 12). These trends extend beneath younger rocks on the southern margin of the district (Soister, 1968; Armstrong, 1970). Normal faulting in the area cuts some of the roll-front deposits and is believed to be Miocene in age (Zeller, 1957). These normal faults are approximately east–west trending and have displacements of 5 to 300 ft (Zeller, 1957).

Uranium deposit types

More than 90 percent of uranium production in the Gas Hills district has been from roll-front deposits (Anderson, 1969), one of four types of known uranium deposits. The two other main deposit types in the district are, in order of importance with respect to ore tenor, transitional-bedded deposits and near-surface oxidized deposits. A fourth deposit type, small and localized high-grade residual deposits, are insignificant in terms of production in the Gas Hills district (King and Austin, 1966; Elevatorski, 1976).

Roll-front deposits

Roll-front deposits are mineral concentrations formed at the boundary between differing physical-chemical conditions, resulting in the accumulation of uranium minerals on one side of that boundary. The primary difference in chemical conditions that results in uranium ore deposition is the presence of a reducing agent, which causes a drop in pH in the water within the potential host rock formation. Oxidizing waters (those with a component of dissolved oxygen) can mobilize and transport hexavalent uranium (U+6). When reducing conditions are encountered on the reduced side of the chemical front resulting in tetravalent uranium (U+4), the reduced form precipitates out of the solution and commonly forms uraninite and coffinite, typically interstitial to and as coatings on the grains of a favorable host rock. Favorable host rocks have high permeability and porosity. Uranium deposits down gradient from the reduction/oxidation boundary are commonly called redox deposits. Redox deposits and occurrences are formed by low temperature geochemical processes. Meteoric water usually contains sufficient dissolved oxygen to oxidize and carry uranium in carbonate or phosphate complexes (Langmuir, 1978). When the oxygen is consumed in the oxidation of pyrite or organic carbon, uranium will be precipitated when it becomes the insoluble reduced tetravalent ion. If pyrite is oxidized, acid will also form, lowering pH. This acid can be neutralized if calcite is present. These chemical reactions can also be facilitated by bacterial action. Within the zone of acidic conditions, adjacent to the mineralized zone and on the convex (down gradient) side of the roll-front (fig. 13), marcasite, ferroselite, and native selenium are deposited (Files, 1970).

As uranium-bearing oxidized groundwater passes through the original host rock, it leaves behind alteration and secondary mineralization. Uranium accumulations on the convex side of the front typically exhibit an irregular, asymmetric distribution of ore that grades from rich ore most proximal to the chemical front, to intermediate ore, and into the more distal weakly mineralized zone referred to as protore (King and Austin, 1966); for example, the light-gray unaltered rock in figure 13. Continued influx of oxygenated water can cause a roll-front to migrate down the groundwater flow gradient as uranium becomes remobilized and redistributed further down gradient in the unaltered rock.

In cross-sectional view, roll-fronts take on a crescent, or “C” shape, with mineralization concentrating on the convex side of the chemical front (fig. 13). Some fronts develop more irregular shapes in vertical section, forming S-shapes or wavy interfaces. In plan view, roll-fronts exhibit a highly irregular, sinuous, and tongue-shaped orientation because of the braided nature of favorable hydrologic conduits interbedded with impermeable shaly units in the subsurface. Since uranium-bearing fluids will most likely follow the most permeable trends of the original fan systems, those fluids will also fan out further down gradient, resulting in merging roll-fronts in some cases (figs. 12, 14), and extensive altered rock horizons up to several hundred feet in cross section (fig. 14).

Roll-fronts almost always exhibit distinct upper and lower limbs containing uranium mineralization, the lower of which are usually longer and thicker (Harshman and Adams, 1981). The limbs are known to extend hundreds of feet up-gradient from the roll-front (Armstrong, 1970). They occur along contacts between the permeable host rock and the overlying and underlying impermeable rocks, typically claystone, siltstone, or shale. Numerous roll-fronts commonly occur throughout a stratigraphic interval of interbedded host rocks and impermeable layers. These en echelon stacks in a frontal system are known to span intervals of up to 300 vertical ft in the central ore trend of the Gas Hills (fig. 14; Armstrong, 1970). Individual roll-front thicknesses in the Gas Hills district generally range from 10–15 ft, but many exceed 20 ft locally (Armstrong, 1970).

Uranium mineralization in the roll-front deposits is epigenetic. This is best demonstrated by the associated alteration and the fact that the ore typically crosscuts bedding. Roll-front uranium occurrences are found at the redox boundary between unaltered sandstone and arkose (in reducing conditions), typically containing organic carbon, pyrite, amphibole, pyroxene, magnetite, and calcite, and altered (oxidized) sandstone, typically containing limonite, hematite, and other oxidized minerals. Uranium is irregularly distributed and may not be present everywhere on the roll-front (Harris, 1982). In an ideal roll-front cross section, uranium is concentrated along the convex side of the redox interface. Uranium concentrations decrease abruptly into barren oxidized rock (altered zone in fig. 13) at the redox interface, and uranium concentrations gradually decrease down gradient in reduced rock (unaltered zone in fig. 13). In addition to uranium, other elements typically concentrated in Gas Hills roll-fronts include selenium, molybdenum, and arsenic (Anderson, 1969).

Transitional-bedded deposits

Transitional-bedded deposits, sometimes referred to as blanket deposits (King and Austin, 1966), are secondary deposits that form as a result of the oxidation and

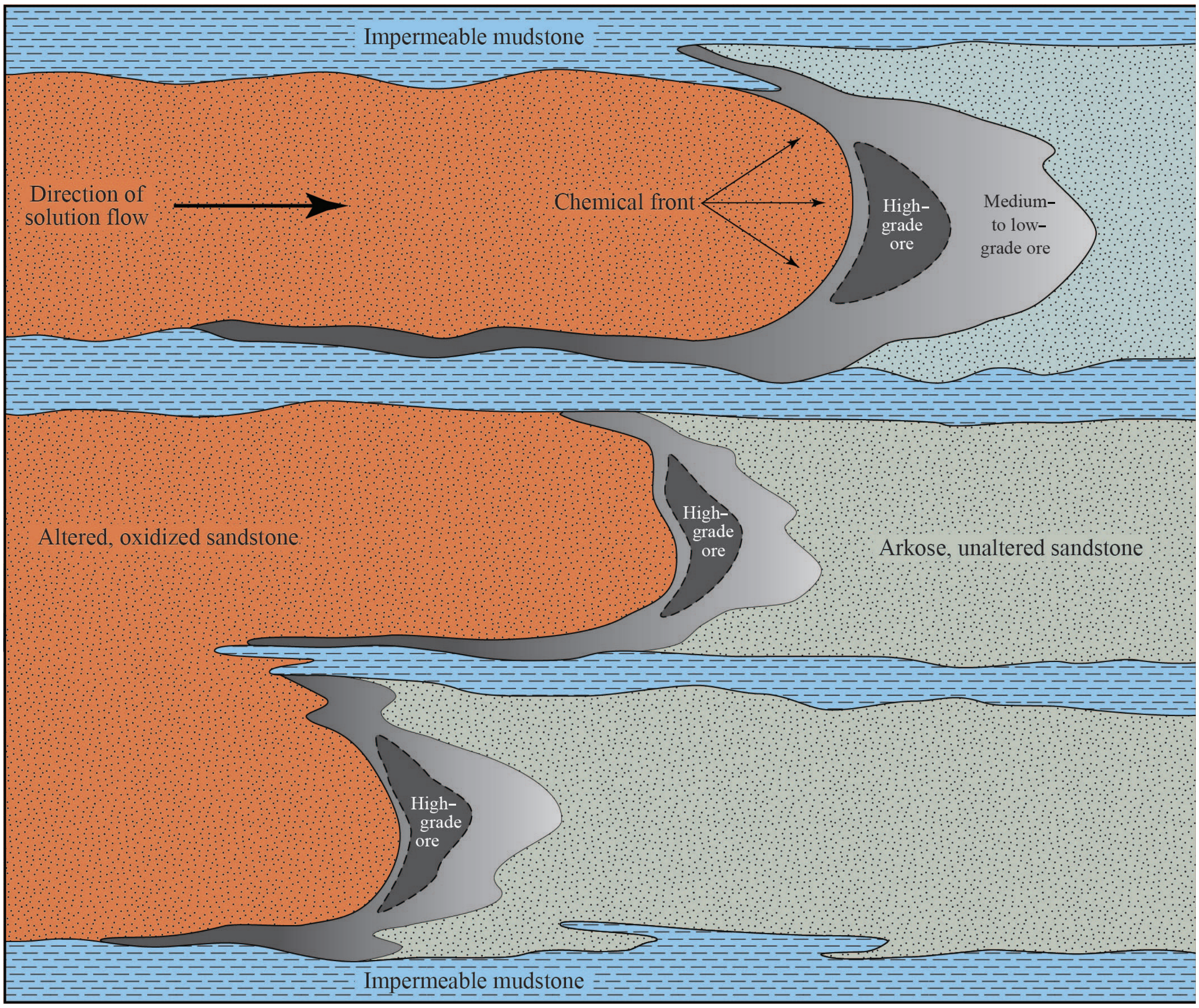

Figure 13. Cross-sectional depiction of en echelon arrangement of a series of roll-front uranium deposits. Modified from Nielsen, 2013.

redistribution of uranium from stratigraphically higher ore deposits. These bedded deposits form when a pre-existing deposit such as a roll-front is oxidized by meteoric processes, and its uranium is redistributed by downward-moving solutions until those solutions encounter a reducing environment somewhere lower along the hydrologic gradient. As with the solutions forming roll-fronts, the distribution of these bedded deposits is a function of favorable water chemistry (both for mobilizing and transporting uranium) and host rock lithology. The ore in this type of deposit was probably precipitated from solution due to reduction in anoxic groundwater or in and around organic debris. Typical host rocks of this deposit type contain interstitial carbonaceous material in sandstones, arkoses, and conglomerates, as well as lignite and carbonaceous shale, providing a reducing setting (King and Austin, 1966). These reducing conditions are often related to less permeable clay and silt layers, hence the bedding of the deposits. Some fault-related damming and perching of water tables is also present in these transitional deposits. Transitional-bedded deposits probably underwent several episodes of oxidation, mobilization, and redeposition. Most deposits of this type in the Gas Hills district occur in the eastern ore trend (Elevatorski, 1976).

Near-surface oxidized deposits

The first deposits mined in the Gas Hills district were oxidized-surface and near-surface ore. These deposits typically contained small tonnages of relatively low-grade ore despite preliminary field indications of high-grade ore. Since these deposits are near-surface and highly susceptible to oxidation, the uranium in them is easily leached and washed away. However, prior to removal by surface waters, the uranium would have had millions of years to decay, resulting in the accumulation of daughter products, many of which are also radioactive. Consequently, a radiation detector may record high counts from daughter product elements rather than from

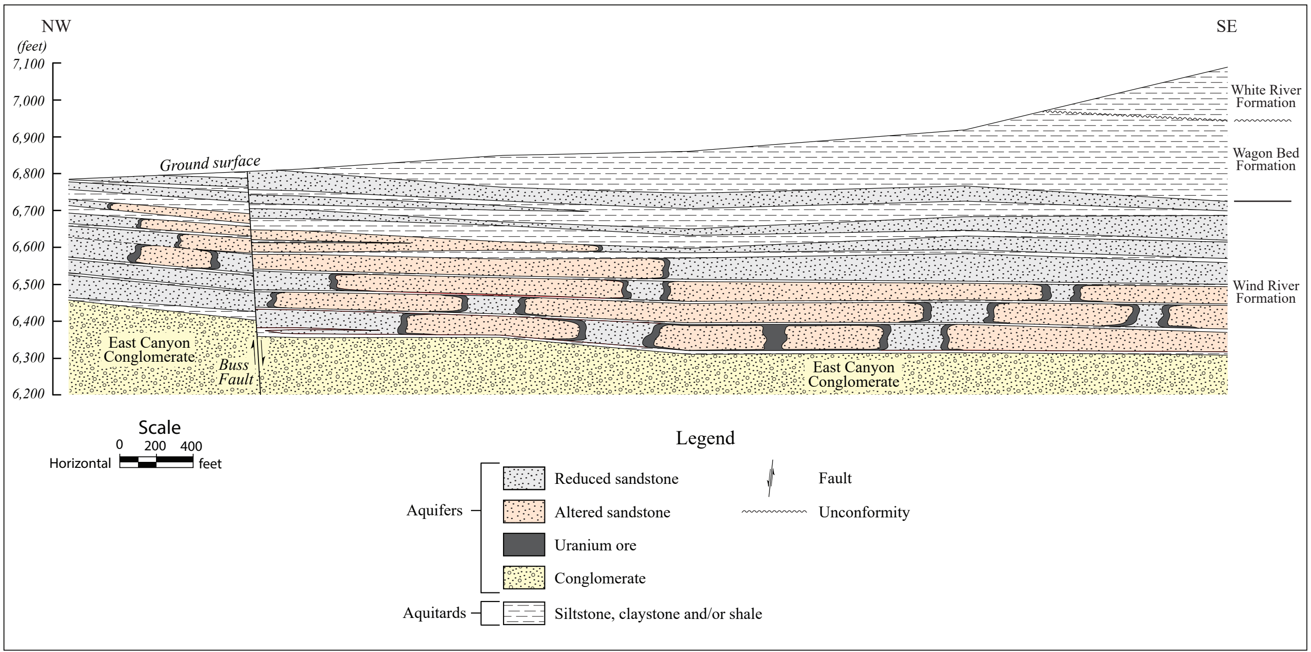

Figure 14. Cross-sectional view of en echelon stacking of roll-front deposits in the Puddle Springs Arkose Member of the Wind River Formation in the eastern Gas Hills. Modified from Power Resources Inc., (1996). As uranium-bearing fluids infiltrate the fan system, the migration of a given roll-front will fan out similar to the development of the original fan system, resulting in some instances of roll-fronts migrating toward each other (bottom ore horizon).

uranium. This condition is called radiogenic disequilibrium. Shallow ores of this type were thus an enigma to the early miners unaware of this phenomenon. The Geiger counters and other similar instruments, such as radiation scintillometers that were used in the early days of mining for ore-grade control, indicated abundant uranium due to high radiation, while the mill reported only low-grade uranium ore. This problem was overcome by chemically analyzing samples of the uranium ore at the mine and calibrating the radiometric readings with these chemical analyses. Modern exploration typically employs a far more accurate technique of determining uranium content surrounding an exploration drill hole. A PFN, or prompt fission neutron probe, selectively measures gamma ray emissions from the ^{235}U isotope. The PFN's detector is not affected by emissions from the daughter elements of uranium decay, and alleviates the problem of disequilibrium when evaluating and estimating resources. The PFN tool is a vast improvement over early exploration when, as described in Anderson (1969), bucket-auger drilling was employed in order to cut drill holes up to 30 inches in diameter, which were "of sufficient size to permit a man to be lowered into the hole where he could accurately sample the ore in place."

Surface ores of this type are composed of common secondary uranium minerals and some reduced uranium minerals, typically uraninite and coffinite, where carbonaceous material was not completely oxidized, often with halos of secondary uranium minerals such as autunite, meta-autunite, and carnotite, as well as minor carbonate-fluorapatite (King and others, 1965). As mining and exploration technology advanced, deeper, larger, and richer unoxidized deposits were discovered.

High-grade residual deposits

A fourth deposit type is found locally in altered sandstone horizons (on the concave side of the roll-front) and is referred to as a high-grade residual deposit. This type of deposit forms when uranium-bearing solutions have encountered such features as thin lignites, carbonaceous shale, or even small accumulations of organic matter (organic trash) such as trees or other plant material. The carbon in this material acts as the reducing agent, precipitating uranium minerals (Elevatorski, 1976), while the bulk of the uranium-bearing fluid continues flowing down gradient until it encounters a reducing environment if present.

Hypotheses on the development of uranium deposits

Ore genesis in the Gas Hills district is widely believed to be the result of uranium-bearing solutions permeating favorable host rocks in the Puddle Springs Arkose Member of the Wind River Formation. However, some geologists have asserted that the host rocks themselves were the source. Snow (1971) postulated that uranium present in arkosic sediments deposited in the Gas Hills district (Puddle Springs Arkose Member) were accompanied by carbonaceous and metallic material, resulting in uranium-bearing protore, where uranium resided in the crystallographic framework of granitic grains of the arkose. Oxygenated water infiltrated these highly permeable sediments and reacted with pyrite, both diagenetic and epigenetic, in the Puddle Springs Arkose Member, causing the migration of acidic chemical fronts down gradient. Uranium was leached by oxidizing water and then precipitated on the reduced side of the chemical front as it permeated the arkoses of the Puddle Springs Arkose Member. This process continued until the flow of groundwater through the system was interrupted, either by faulting or lack of water input, in the late Quaternary (Snow, 1971).

Love (1971) argues that uraniferous lacustrine beds in the Miocene Moonstone Formation are the primary uranium source of the Gas Hills deposits. Love (1971) cites a 1-ft-thick bed within the Moonstone Formation that contains roughly 200 tons of uranium per square mile as well as the fact that water in that formation contains triple the amount of dissolved uranium as that of other rock units outside of the regional uranium districts, including those at Crooks Gap and Shirley Basin. He also notes oil staining in rocks of Eocene, Oligocene, and Miocene age regionally, and especially in the vicinity of the uranium districts. The combination of migrating hydrocarbons (with associated pyrite in the host rock) and the influx of uranium-bearing waters from the Moonstone Formation may have led to the accumulation of the Gas Hills (and other) deposits (Love, 1971). Uranium was concentrated, at least in the Gas Hills, due to the gentle east-trending arch that developed in the southern part of the Wind River Basin during the Miocene, which tilted the Wind River Formation in the district just slightly to the south-southeast. The pinch-out of permeable rocks to the west combined with upland barriers to the east led to the tight concentration of deposits in the Gas Hills district (Love, 1971).

Using three-dimensional modeling from drill hole log data in the eastern ore trend at the Buss pit, Long (2014) concluded that hydrocarbons migrating along pre-mineralization fault conduits established reduction zones in permeable rocks adjacent to the faults. Long (2014) concluded that uranium mineralization occurred as uranium-bearing groundwater flowing down gradient in the host formation interacted with reduced water along the fault system. While this model seems to account for much of the mineralization patterns at the Buss mine (Long, 2014), numerous other deposits in the Gas Hills district lack similar structures, indicating the importance of additional factors regarding the reductant(s). The complete nature of the factors controlling reduction remains partially unclear, but hydrocarbons seem possible, at least in some parts of the Gas Hills district (Long, 2014). However, carbonaceous material, whether pre-existing in the host rock or introduced after deposition, seems an important component as well.

Common to all of the scenarios described above is the presence of an in-situ reductant encountered by oxidized, uranium-bearing groundwater flowing in a general northward direction through the Puddle Springs Arkose Member of the Wind River Formation. The source of the uranium transported to the host rock remains unclear, but two proposed sources have received the most attention, as well as a combination of the two.

Source of uranium

Precambrian rocks of the Granite Mountains

Uranium provinces around the world are usually found spatially associated with Precambrian rocks (Dahlkamp, 1993). Wyoming is a uranium province (Boberg, 2010), and the location of the major uranium mining districts around the central part of the state supports the likelihood of their genetic relationship with granitic masses such as the Granite Mountains and possibly the northern Laramie Range, both of which are considered part of the Wyoming batholith (Bagdonas, 2014; Bagdonas and others, 2016). At 11.5 ppm and 8.6 ppm, respectively, the biotite and the leucocratic granites of the Granite Mountains have uranium concentrations two to three times that of average granites (Boberg, 2010). Two prominent periods of uranium loss have affected the Granite Mountains; the first occurred during a Proterozoic metamorphic event at proximately 1,400–1,700 Ma and the second was during Laramide deformation, which exposed the batholith in central Wyoming. Rosholt and others (1973) measured the amount of uranium and radiogenic lead in samples from the Granite Mountains and calculated that their samples were about 75 percent depleted of original uranium content, beginning by early Cenozoic time. The climate during the early Cenozoic period was tropical to subtropical, a setting that would expose the Granite Mountains to more enhanced chemical weathering than the conditions that have prevailed since the Eocene (Houston, 1969). Rosholt and others (1973) concluded that this episode of uranium loss represents the major source of uranium in the Gas Hills and other districts of central Wyoming. Nearby districts include the Shirley Basin, Great Divide Basin, and Crooks Gap-Green Mountain areas (fig. 1).

Cenozoic tuffs

Following the findings of Denson and others' (1951) work on uranium deposits in South Dakota, Love (1952) proposed that ash fall tuffs in the Oligocene White River Formation were the source for uranium deposits in the underlying Wasatch Formation. Denson and others (1951) concluded that tuffs of the overlying White River Formation supplied uranium occurring in lignites in western South Dakota. Love (1952) went on to suggest that such tuffaceous deposits could be the source for other uranium deposits in Cenozoic sedimentary basins in Wyoming given their originally thick and widespread distribution across Wyoming and the Rocky Mountain foreland. With respect to the Gas Hills deposits, the Miocene Moonstone Formation, the erosional remnants of which lie approximately 15–20 miles south of the Gas Hills district, was hypothesized to have supplied uranium to the district (Love, 1971).

Studies of volcanic glass in ash fall tuffs have demonstrated that uranium is easily liberated and mobilized after dissolution of volcanic glass and transported into the groundwater system soon after saturation from meteoric processes (Zielinski, 1980, 1983; Walton and others, 1981). In one study, uranium was determined to be localized in siliceous gel and concentrated in amorphous silica agates during dehydration of lacustrine sediments near the base of the White River Formation in the Shirley Basin (Zielinski, 1977). Subsequent weathering and erosion of such material would then likely transport uranium to favorable host rocks. Another similar hypothesis is that since ions readily adsorb to the surface of fresh volcanic ash shortly after eruption, early meteoric saturation of the ash results in uranium easily mobilized into solution and transported to a favorable host rock setting (Taylor, 1969; Boberg, 2010).

The White River Formation was once vastly more widespread than its current distribution. Its thickness and areal extent is calculated to have contained approximately 100 times the amount of uranium needed to account for the estimated uranium content in the deposits of the Cenozoic sedimentary basins of Wyoming (Zielinski, 1983; Boberg, 2010). Additionally, Granger and Warren (1978) pointed out that along with uranium, selenium is also commonly associated with uranium deposits in the Gas Hills district and in the overlying tuffaceous sedimentary rock strata, namely the White River Formation. Coleman and Delevaux (1957) cited selenium content in the Wind River Formation and conclude that it derived from the overlying tuffaceous units.

Combined source

It is possible that both Precambrian granitic rocks and basin-filling ash fall tuffs contributed uranium to the Gas Hills ore deposits. Massive amounts of Precambrian material was stripped from the Granite Mountains, with accompanying uranium loss, during the Cenozoic. Paleogene chemical weathering and erosion of the Granite Mountains feeding the surface and subsurface hydrologic systems at the time would have likely been neutral or slightly basic, carrying hexavalent uranium down gradient into the surrounding sedimentary basins, most of which contain uranium ore deposits. Additionally, those same basins were once blanketed—along with all but the highest peaks of the Granite Mountains—with hundreds of feet of Oligocene and Miocene sediments, much of which contained adequate amounts of uranium-bearing tuffaceous material to account for uranium deposits in the Gas Hills and other districts. Surface or groundwater encountering reductants in the Puddle Springs Arkose Member deposited uranium there regardless of the ultimate source. The timing of the mineralization itself may tend to favor one source while not ruling out the other.

Age of the uranium deposits

Emplacement of uranium deposits in the Gas Hills district is likely not contemporaneous with the host rocks in the Puddle Springs Arkose Member. Uranium entered the Puddle Springs Arkose Member neither as a constituent of the sediment flow nor as a diagenetic product of the arkosic host rock. The morphology of roll-fronts indicates that uranium ore formation is a result of the infiltration of mineralizing groundwater processes, but differing hypotheses on the timing of mineralization have been proposed.

Zeller (1957), Cheney and Jensen (1966), Anderson (1969), and Love (1970) proposed ages for the mineralization of uranium deposits as young as Pleistocene to recent. Houston (1969) maintained that late Pliocene regional uplift caused shifting of the groundwater gradients and subsequent flow vectors such that uranium-bearing solutions were diverted to and/or trapped in reducing environments. Furthermore, Houston (1969) suggested that pre-existing uranium deposits may have been dissolved and redistributed as oxidizing fluids permeated new areas. Dooley and others (1974) dated a sample from the Lucky Mc mine at approximately 22 million years (Ma). Childers (1974) and Rackley (1976) hypothesized that uranium was mobilized and concentrated between 28 and 40 million years ago. The best estimate for the timing of mineralization of the uranium deposits in the Gas Hills district is between 26 and 43 Ma (Ludwig, 1979). Ludwig's findings reinforce the work of Childers (1974) and Rackley (1976), and dismiss most of the earlier estimates based on studies of U-Pb isotopic apparent ages of uraninite and coffinite samples from the Gas Hills and from the Crooks Gap mines on the south side of the Granite Mountains. The subtropical conditions most favorable for the mobilization of uranium would have terminated near the end of the Oligocene (Childers, 1974; Rackley, 1976).

GAS HILLS DISTRICT HISTORY

Events leading to uranium discoveries in the Gas Hills

Uranium mining in Wyoming began in the early 1950s at mines in the northwestern Black Hills area of Crook County. Conventional wisdom around that time held that uranium was associated with hydrothermal activity. However, the discovery of uranium deposits not associated with such hydrothermal settings, but rather in

Cenozoic sedimentary basins, called into question that model (Love, 1952). Denson and others (1951) examined uraniferous lignites in South Dakota, a setting in which there was no connection to hydrothermal processes, and postulated that the uranium seeped into the lignites as a result of leaching from overlying tuffaceous sediments of Oligocene age. With this leach hypothesis in mind, U.S. Geological Survey geologist David Love sought to find new uranium deposits in Cenozoic sedimentary basins in association with similar tuffaceous beds. In the spring of 1950, Love recommended aerial radiometric surveys of parts of the Powder River Basin in northeast Wyoming, particularly the Pumpkin Buttes area of southwestern Campbell County; the surveys were conducted in October 1950 (Love, 1952). Several anomalous spots were identified, and upon field investigation with a scintillometer, Love and his associates, Richard Hose and Franklin Van Houten, discovered a rich roll-front deposit at the surface along with several other uranium deposits. Six samples taken from their initial discovery averaged 15.14 percent uranium (Love, 1952). In the wake of this significant discovery and apparent confirmation of the ash-leach hypothesis, numerous uranium discoveries were made, not only in the Pumpkin Buttes area but in several other Cenozoic sedimentary basins of Wyoming.

Early discoveries

Following the discovery in the early 1950s of uranium in Paleogene-aged rocks at Pumpkin Buttes and Miller Hill in Campbell and Carbon counties, Wyoming, respectively, geologists at the U.S. Geological Survey and the U.S. Atomic Energy Commission believed that similar correlative rock units in the Gas Hills area also warranted field investigations (Love, 1954). In late September 1953, they initiated scintillation counter surveys and found numerous radioactive anomalies in the Eocene Wind River Formation. They also learned that about two weeks earlier, a prospector named Neil McNeice and his wife Maxine made the very first discovery of radioactive sandstone in sec. 22 of T. 33 N., R. 90 W., at an oxidized surface exposure of uranium-rich sandstone in the Wind River Formation (Love, 1954). A monument to the McNeice find stands at the site of that discovery (fig. 15). The discoveries by the McNeices and Love were made independently of one another, as well as a third, by Page Jenkins and his partner Darby Hand, at around the same time in the eastern Gas Hills (Snow, 1978).

Niel McNeice partnered with L.A. Morfeld and together staked claims that would become the well-known Lucky Mc mine. They built the Lucky Mc mill nearby a few years later. The Lucky Mc mine in the central part of the district became one of the most productive in the Gas Hills. Soon after McNeice's discovery, other prospectors staked their claims in the central Gas Hills, including H.C. Meyer, J. Bansept, and C.L. Scott, all by the end of October 1953 (Snow, 1978). A rush for uranium in the Gas Hills district was on.

Figure 15. A large pillar of oxidized uranium ore at the site of the McNeice discovery in September 1953.

McNeice, Morfeld, and other associates formed the Lucky Mc Uranium Corporation, 60 percent of which was purchased by Utah Construction in 1953, who would purchase the remainder of the company seven years later. The Lucky Mc Uranium Corporation was renamed Pathfinder Mines Corporation in 1978 (Snow, 1978). Utah Construction became Utah International in 1971, and its uranium mining and milling operations became a subsidiary of Utah International in 1978 under the name Pathfinder Mines. A controlling interest in Pathfinder Mines was purchased in 1982 by COGEMA, a French nuclear mining, processing, and fabrication company. Numerous other entities staked thousands of additional claims in the district in the coming weeks and by mid-November 1953, 11 separate groups of claims had been staked in the three main sub-districts (western, central, and eastern ore trends) of the Gas Hills district (Snow, 1978). The Wyoming Mining Association in April 1956 listed nearly three dozen companies as actively mining or developing properties in the greater Gas Hills area (Snow, 1978).

West of the Lucky Mc area, P.T. Jenkins and H. D. Hand soon staked claims on radiometric anomalies (George, Stan, and Dick claims) and formed Jenkins and Hand Mining (later Globe Mining Company). Other early claim-stakers in the western Gas Hills included Marion and Charles Roripaugh (Clifford group claims), Stanleigh Starrett (Hal, Bart, Eagle, and Skoal group claims), and Cotter Ferguson (Bullrush area; Snow, 1978).

Thermopolis tractor dealer Alfred Nostrum revisited an area in October 1953 where he remembered seeing "rusty yellow rock" and made claims on what was to become the Aljob mine area in the eastern portion of the Gas Hills district (Snow, 1978). All of these discoveries were made and claimed by mid-November 1953. Some of the above mentioned areas in the Gas Hills district have not been fully mined out and still contain significant resources.

Mining and production

Uranium mining in the Gas Hills district began in 1954 from several mines in the district. Uranium ore was initially shipped via truck and rail to Vitro Uranium Corporation's mill in Salt Lake City, Utah, and to a U.S. Atomic Energy Commission (AEC) buying station in Edgemont, South Dakota. In March 1956, the AEC established an ore buying station in Riverton, Wyoming, significantly reducing transportation costs for the mining companies. Table 1 lists the approximate annual production totals from the Gas Hills mines.

The large amount of ore mined from the Gas Hills district in the late 1950s demonstrated the need for milling capacity to process ore into concentrated uranium oxide (U_3O_8 or yellowcake). The first uranium mill in Wyoming was constructed by Western Nuclear, Inc. at Jeffrey City, which commenced operations in 1957. That mill had an initial capacity of 440 tons per day (tpd) and processed ore from the Gas Hills district as well as from mines at Crooks Gap, approximately 9 miles to the south. Ore was hauled by truck to the Split Rock Mill from both mining districts. The first mill constructed in the Gas Hills district was the Lucky Mc mill, near the Lucky Mc mine (fig. 16). It began operations in 1958 and had an initial capacity of 750 tpd. The Lucky Mc mill ceased operations in 1988.

The Lucky Mc mill processed approximately 12 million tons of ore from the nearby mines from 1958 until 1988 (U.S. Nuclear Regulatory Commission, 2009). The site of the former Lucky Mc mill is currently under the control of the U.S. Department of Energy (DOE) for long-term surveillance, which includes inspections, monitoring, and maintenance. Figure 17 shows the locations of the mills in the Gas Hills district and their proximities to Jeffrey City and Riverton.

The second mill in the Gas Hills district was built by Federal Radorock-Gas Hills Partners (later Federal American Partners, then American Nuclear Corporation)

Table 1. Production from Gas Hills district mines. 1954–1976 production numbers are from Snow (1978). Italicized U_3O_8 production numbers (1977–1987) are estimates based on average ore grade calculation of Snow's values for 1955–1976 and have been rounded to the nearest 1,000 pounds. The average ore grade used in the calculations is 0.2 percent, in approximate agreement with that of Crew (1969).

Production year	Tons mined	Pounds of U_3O_8
1954	5,000	20,000
1955	20,275	85,300
1956	76,411	343,900
1957	237,726	1,105,400
1958	504,911	2,424,000
1959	680,772	3,148,300
1960	1,040,016	4,884,500
1961	1,019,385	5,094,000
1962	896,986	4,063,400
1963	785,778	3,588,400
1964	710,521	3,165,900
1965	798,761	3,277,800
1966	683,165	3,139,800
1967	866,446	3,465,800
1968	1,256,570	3,769,700
1969	1,097,381	3,731,100
1970	1,200,433	3,985,400
1971	1,044,326	3,446,300
1972	1,139,906	4,331,600
1973	1,067,326	3,796,700
1974	946,106	3,793,900
1975	1,237,131	3,958,800
1976	1,253,365	3,917,500
1977	1,435,627	*5,744,000*
1978	1,482,308	*5,928,000*
1979	1,634,552	*6,536,000*
1980	1,584,252	*6,336,000*
1981	1,144,569	*4,580,000*
1982	798,473	*3,192,000*
1983	878,166	*3,512,000*
1984	549,125	*2,196,000*
1985	136,759	*548,000*
1986	0	*0*
1987	99,318	*396,000*
TOTAL	28,311,846	111,505,500

in the western Gas Hills district and began operations in 1960 with a capacity of 522 tpd (Snow, 1978). The mill operated from 1960–1982 before being dismantled by 1994. Another mill was built in Riverton in 1960 by Fremont Minerals (later Susquehanna-Western Nuclear) with a capacity of 724 tpd. The Susquehanna site also processed ore from the Gas Hills district mines and operated from 1958 until 1964. The third mill in the district was built in the eastern Gas Hills area in 1959 by Globe Mining (later Umetco). Yellowcake production at that site started in 1960 with an initial capacity of 492 tpd (Snow, 1978). This mill operated until 1984 when it was put on standby status. Reclamation of the site was completed in 2006 (U.S. Nuclear Regulatory Commission, 2009). This facility processed uranium ore mostly from the pits in the eastern portion of the district. Historical heap leach and tailings piles sites are now covered with large riprap boulders on the surface to prevent erosion of the underlying protective layers, which include a radon barrier, filter layer, frost protection layer, and top soil (U.S. Nuclear Regulatory Commission, 2009).

Figure 16. McNeice, left, and Morfeld stand next to the first barrel of yellowcake produced at the Lucky Mc mill, the first built in the district. Photo by Bob Peck, 1958, courtesy of the Riverton Ranger newspaper.

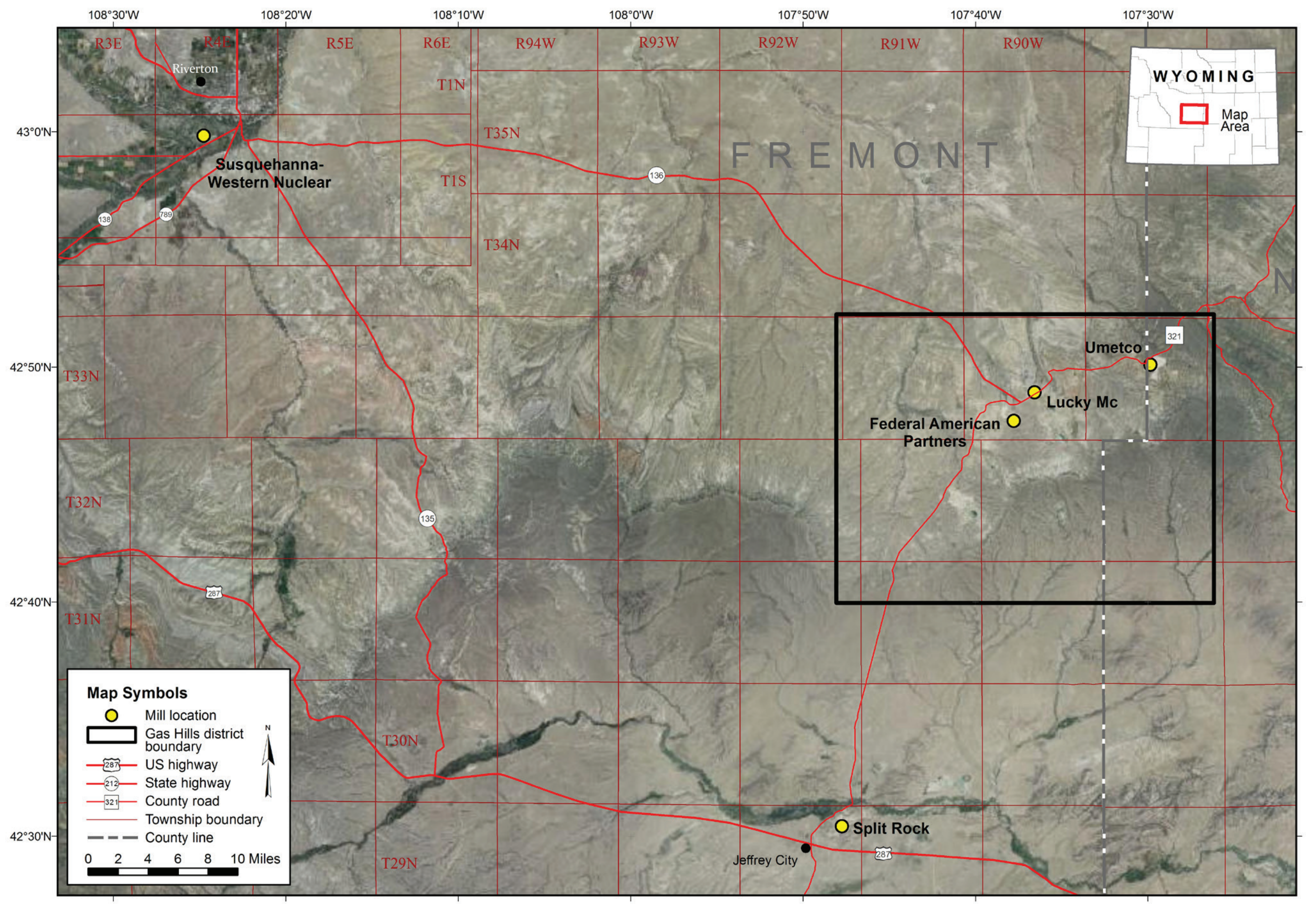

Figure 17. Uranium mill site locations in Fremont County, Wyoming, (plus one mill just inside the Natrona County line) operating by the early 1960s.

Most of the ore produced from the Gas Hills district was mined from surface operations. The smaller near-surface oxidized deposits were often extracted by earth-moving equipment. Other deposits were of high enough grade and depth that they were mined underground, but small tonnages and depth limited their profitability. A major exception is the Peach shaft, which produced nearly 92,000 tons of ore between 1963 and 1967 (table 2). In addition, small underground workings were commonly made in the pit walls of the larger surface mines.

From 1954, when uranium was first mined in the Gas Hills, until 1978, this uranium district was Wyoming's largest uranium producer. Production would increase to a peak of about one million tons in 1960 followed by a decrease through the 1960s. The somewhat depressed uranium market affected other areas more drastically; for example, mining in the Powder River Basin came to a virtual standstill. By 1968, in response to the numerous nuclear power plants coming online, the uranium market had begun to pick up and the higher price for a pound of uranium oxide led to the uranium boom of the 1970s. More than 1.6 million tons of ore were mined from the various Gas Hills district operations in 1979, the record year for this second boom (table 2). From 1978 until 1982, the Gas Hills district was second in production in Wyoming only to the southern Powder River Basin uranium district. In 1982, the Gas Hills district was again the top uranium producer in Wyoming.

Uranium prices began declining in the early 1980s following the Three Mile Island accident, yet the mines of the Gas Hills remained productive. With the downturn in uranium prices, the Gas Hills district in 1983 was again second in production to the mines of the southern Powder River Basin. The last mine in the Gas Hills district (Pathfinder) closed in 1984 and the Pathfinder mill, controlled by COGEMA, was closed for modernization. This mill reopened in 1987, processing small amounts of ore stockpiled at various mines around the Gas Hills district and in the Crooks Gap area. Of note is the fact that the first mill to operate in the Gas Hills, the Lucky Mc, was the last one operating in the Gas Hills, and it was one of the two operating conventional mills in Wyoming in 1987. This mill was closed again in 1989, and there has been no production since that time.

Uranium prices rebounded in the mid-2000s, peaking in 2007 at more than \$137 per pound U_3O_8, and numerous mining companies again began evaluating uranium deposits and planning for the resumption of production. Several deposits in the Gas Hills district still contain considerable resources, and two companies currently have several operations in various stages of application and licensing. URZ Energy acquired several properties from Energy Fuels in summer 2017, and Cameco, a major international uranium producer, has held properties there for several years.

FUTURE URANIUM MINING POTENTIAL OF THE GAS HILLS DISTRICT

Activity in the district since 1989, though mostly in the last 10 years, has been restricted to reclamation of surface pits and, more recently, exploration and delineation drilling at the various deposits still remaining.

Property owners

There are four primary interest holders in the Gas Hills district (fig. 18). Two uranium mining companies are currently developing or evaluating uranium deposits on claims and leases in the Gas Hills. Power Resources, a subsidiary of Cameco Corporation, has filed an application for a permit to mine with the WDEQ's Land Quality Division (WDEQ-LQD Permit to Mine Application No. 687, rev. November 2012). URZ Energy acquired Strathmore Minerals' properties in July 2017 and continues to evaluate the deposits. UCOLO, a wholly-owned subsidiary of URZ Energy Corporation, controls three properties in the western Gas Hills district (Bullrush, Day Loma, and Loco-Lee), and one each in the central and eastern Gas Hills, George Ver and Rock Hill, respectively. URZ Energy merged with Azarga Uranium in July 2018 but remains in control of the Gas Hills properties. Power Resources (Cameco Corporation) owns several properties (Mine Units 1–5) in the central and eastern Gas Hills, and includes two historic shafts, the Peach Lisbon in Mine Unit 3 and the UPZ shaft in Mine Unit 2. A third company, Ur-Energy, acquired 1,816 acres of patented ground in the western and central Gas Hills areas in December 2013. This acreage contains approximately 4,700,000 pounds of eU_3O_8 based on historical resource estimates made by previous mine companies (J. Bonner, written commun.). The fourth company, Anfield Energy, Inc., holds claims and State of Wyoming leases and has not released any information on resource evaluation.

Resource estimates

Resource estimates for the above mentioned companies are available in different formats, some more detailed than the other, but the two primary stakeholders both provide total estimated resources for their respective properties based on historical and recent drilling, testing, and assays. Additionally, both companies control claims and leases on areas that have not been adequately evaluated for NI 43-101 compliant resource estimates. The data presented below were obtained from company websites and reports filed with various regulatory agencies and are the most current available at the time of this writing.

Table 2. Gas Hills district mine data. Latitude and longitude locations were assigned to near the center of the mine area and are approximate. Many mines were acquired and merged with subsequent operations and may have been referred to by more than one name. Also as a result of mergers and acquisitions, some production may have been combined and thus may not be exact. Production figures are from a variety of sources, most notably the Wyoming State Department of Revenue (ad valorem tax records) and the Wyoming State Inspector of Mines. Not all mines produced continuously from initial year to last known year of production.

Mine name	Mine/Site synonym(s)	Latitude	Longitude	Township	Range	Section	Mine type	Original operator	Last Known operator	Year of initial production	Last known year of production	Reported production (short tons)
School Section mines	Levi	42.832147	-107.51096	33	89	16	Surface	D. Levi	D. Levi	1956	1965	182,122
Lucky Mc and Green River Mines		42.819	-107.582	33	90	23	Surface/Underground (minor)	Lucky Mc Uranium Company	Cogema	1954	1987	11,850,639
Star		42.82486	-107.47249	33	89	14-23	Surface	Uranium Mining, Globe Mining	Union Carbide	1954	1980	224,999
Blarco		42.761	-107.679	32	91	12	Surface	Mountain Mesa Uranium	J.M. Wade	1954	1965	2,376
Last Chance	Bay L	42.781	-107.6205	32	90	4	Surface	San Juan Uranium	San Juan Uranium	1954	1954	32
Ridge 1 and Teton	Wentz	42.889744	-107.452308	34	89	25	Underground	Northwest Uranium	Northwest Uranium	1955	1965	12,726
Rim	Red Horse 3	42.846639	-107.530849	33	89	8	Surface/Underground (minor)	San Juan Uranium	Utah Construction	1955	1967	228,782
Blue Buck and Red Horse	Rock Hill	42.846553	-107.511013	33	89	9	Surface	A. Ellerby	H.M. Purcel	1955	1964	3,477
Hope	Hope-Star	42.769	-107.67	32	91	1	Surface	Noramco	Western Nuclear	1955	1972	5,272
Idiots Delight		42.7538	-107.669	32	91	12	Surface	Lander Uranium; Mohawk Uranium Corp.	Lander Uranium; Mohawk Uranium Corp.	1955	1955	32
Union Carbide West Gas Hills Mine	George, G-1, G-2; Dick, D; Ola, K; Joy, E; Phil, Dee, P	42.7788	-107.656	33	90	32	Surface/Underground (minor)	Numerous	Union Carbide	1955	1983	4,007,894
TVA west Gas Hills Mine	Cal, Sagebrush-Tablestakes, Federal, Sunset, Andria, Clyde-Bret-Loco	42.781	-107.653	32	90	6	Surface/Underground (minor)	Numerous	Federal American Partners	1955	1981	3,278,685
Bountiful	Redwood	42.803014	-107.491754	33	89	27	Surface	Two States Uranium	Union Carbide	1956	1964	66,662
Ran Rex	Tee	42.8214	-107.4814	33	89	23	Surface	Ran Rex Mining	Federal American Partners	1956	1974	295,797
Thunderbird (Fanny May)	Fannie Mae, Fanny May	42.846553	-107.452531	33	89	12	Surface	PC Mining	Union Carbide	1957	1965	43,469
Pix-Veca		42.817532	-107.491737	33	89	22	Surface	Veca Minerals Company	Federal American Partners	1957	1969	106,550
Skyline		42.8805	-107.4648	34	89	35	Underground	Northwest Uranium	Northwest Uranium	1958	1959	247

Table 2 continued.

Mine name	Mine/Site synonym(s)	Latitude	Longitude	Township	Range	Section	Mine type	Original operator	Last Known operator	Year of initial production	Last known year of production	Reported production (short tons)
Eureka		42.8083	-107.6565	33	90	29	Surface/Underground (minor)	Northwestern Oil	Washakie Uranium	1958	1959	3,606
	Imperial											
Day, Loma		42.731	-107.671	32	91	24	Surface/Underground (minor)	Federal American Partners, US Energy	Centurion Nuclear	1958	1982	1,045,488
Fraiser Lamac		42.8027	-107.5867	33	90	26	Surface	Western Nuclear	Western Nuclear	1959	1977	621,700
	Sateco, Vitro											
Buss		42.817532	-107.491737	33	89	22	Surface	Federal American Partners	Federal American Partners	1959	1980	104,395
	Tee, Russ											
Clyde-Brett-Loco		42.741	-107.685	32	91	23	Surface/Underground (minor)	Federal American Partners	Federal American Partners	1960	1979	1,596,781
Union Carbide East Gas HIlls MIne		42.817532	-107.491737	33	89	22	Surface/Solution	Federal American Partners	Union Carbide	1963	1983	988,309
	Tee; Pix; Mars; Buss; Pay; Aljob; Star											
Peach-Lisbon Shaft		42.772264	-107.587708	32	90	3	Underground	Atlas Minerals	Atlas Minerals	1963	1967	61,957
Wild Goose 5, 6 mines		42.7638	-107.651	32	90	7	Surface	Utah Construction	Utah Construction	1963	1964	18,251
	Kiewit											
Rex		42.7604	-107.6932	32	91	11	Surface	Rex Mining	Federal American Partners	1965	1969	24,825
Jack No.2 claim mine		42.770941	-107.676991	32	91	1	Surface	Globe Mining	Globe Mining	1956	1956	1,394
Nels		42.7385	-107.67	32	91	13-24 LINE	Underground	Globe Mining	Western Nuclear	1962	1973	4,523
Stan		42.7963	-107.6188	33	90	27-28-33-34	Surface	Jenkins and Hand	Globe Mining	1955	1957	6,670
Rox		42.8232	-107.5017	33	89	21	Surface	Globe Mining, Union Carbide	Western Nuclear	1965	1972	68,836
Bullrush		42.8	-107.65	33	90	29	Surface	Savanna Construction Co.	Western Nuclear	1955	1965	286,630
Sagebrush No. 1		42.793	-107.642	33	90	32	Surface	Long Mining, Gas Hills Uranium	Federal American Partners	1955	1980	950,006
	Tablestakes										Total	26,093,132

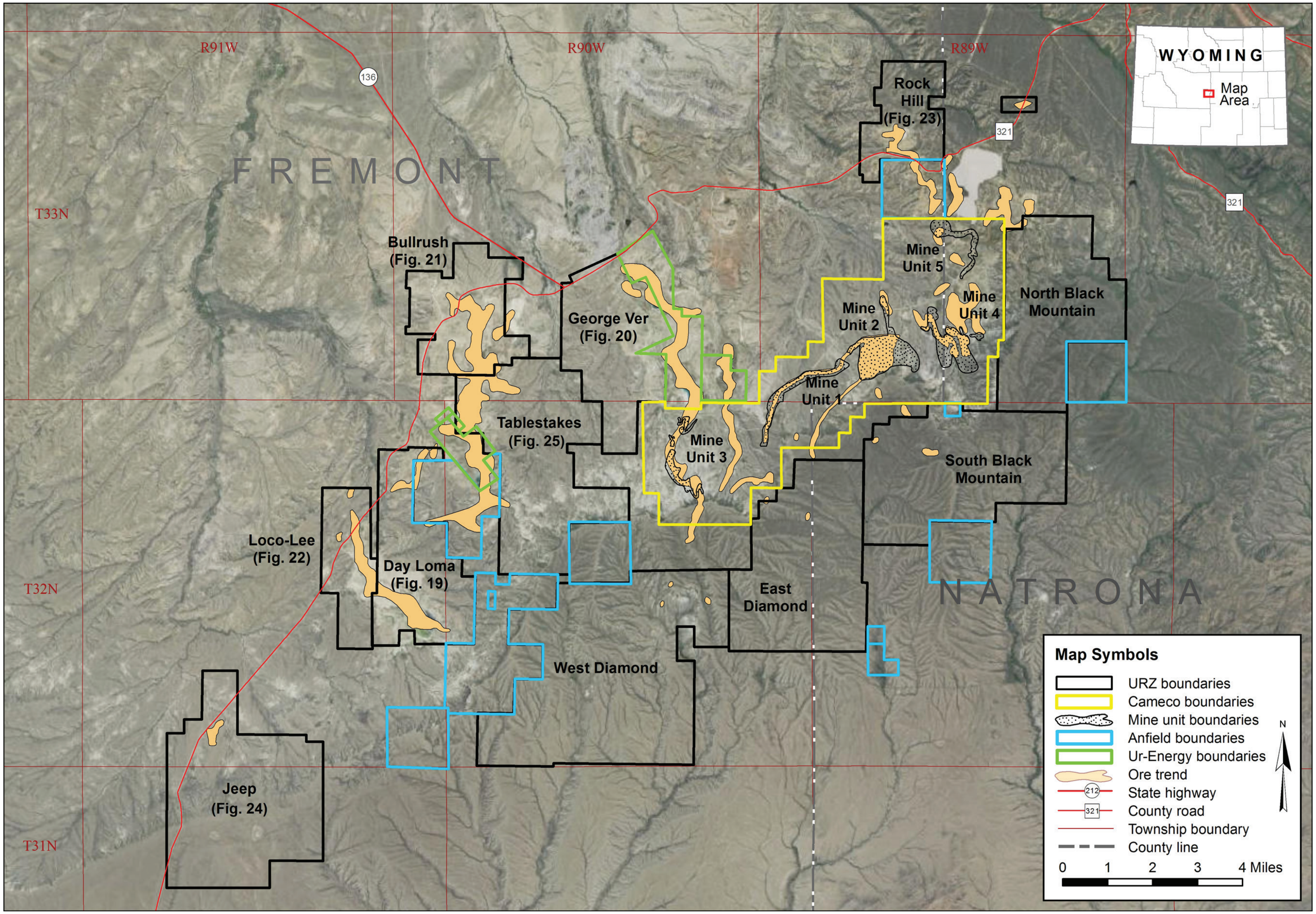

Figure 18. Properties controlled by URZ Energy, Cameco, Ur-Energy, and Anfield Energy. Figures 19 through 25 show areas of primary, historical, and exploration targets. Modified from Power Resources Inc., (1996) and Nielsen and others (2013).

Primary development targets

The primary development targets controlled by URZ Energy Corporation (UCOLO) for future uranium mining in the Gas Hills district (roughly from southwest to northeast) are the Loco-Lee, Day Loma, Bullrush, George Ver, and Rock Hill deposits. Future mining at these locations would primarily be continuations along historical trends. Based on drilling and assaying as of March 2013, Nielsen and others (2013) estimate remaining resources (indicated and inferred NI 43-101 compliant, as defined by Canadian National Instrument 43-101 Standards of Disclosure for Mineral Projects by the Canadian Securities Administration) in these five deposits to be approximately 10.9 million pounds equivalent U_3O_8 (eU_3O_8) using grade-thickness contour calculations (table 3). Figures 18–23 depict claim ownership at the time URZ Energy acquired these areas in July 2017. Claims are maintained on an annual basis and thus current claim ownership status may vary. The resource estimates presented in table 3 are based on data analyzed within the boundaries shown in figures 18–23.

Beahm (2017) reports NI 43-101 compliant indicated plus inferred resources for URZ Energy of approximately 7.26 million pounds (table 4). Slight differences in methods and/or initial parameters and assumptions probably account for the disparities between Beahm (2017) and Nielsen and others' (2013) estimates, but

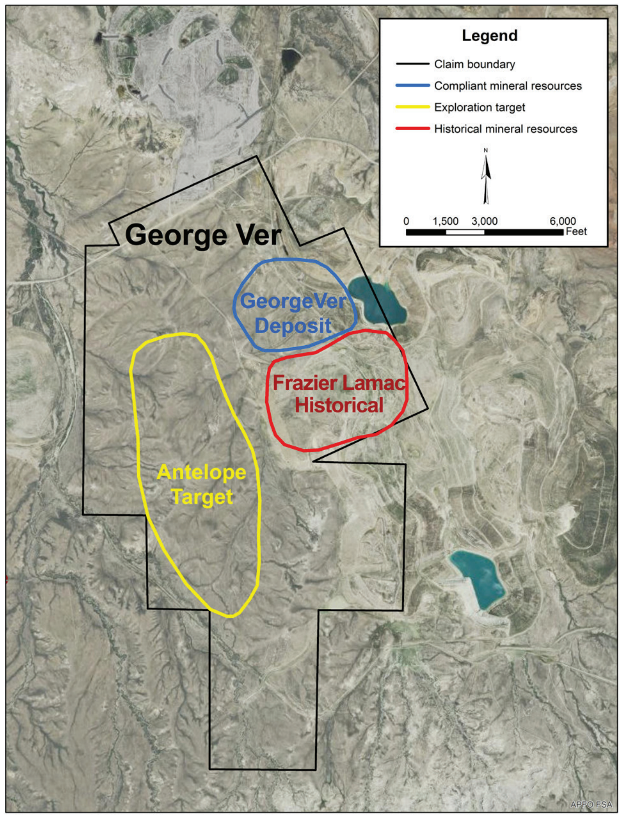

Figure 20. George Ver property (above right), SE1/4, T. 33 N., R. 91 E., modified from Nielsen and others (2013).

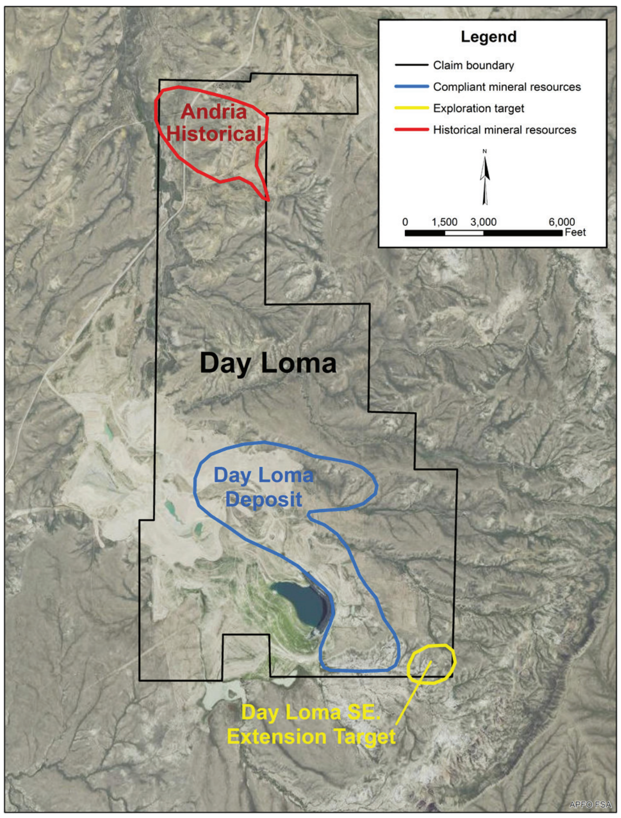

Figure 19. Day Loma property (above left), E1/2, T. 32 N., R. 91 E., modified from Nielsen and others (2013).

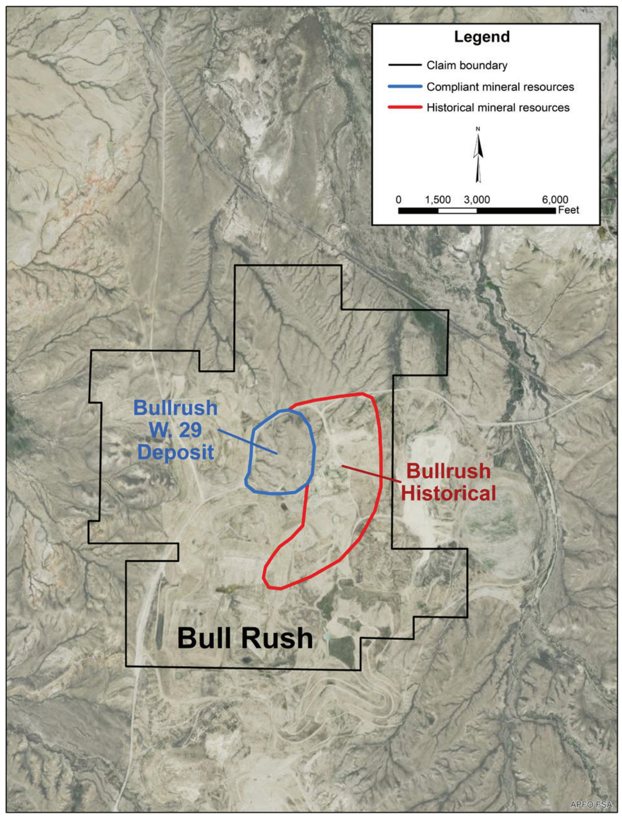

Figure 21. George Ver property (above right), SE1/4, T. 33 N., R. 91 E., modified from Nielsen and others (2013).

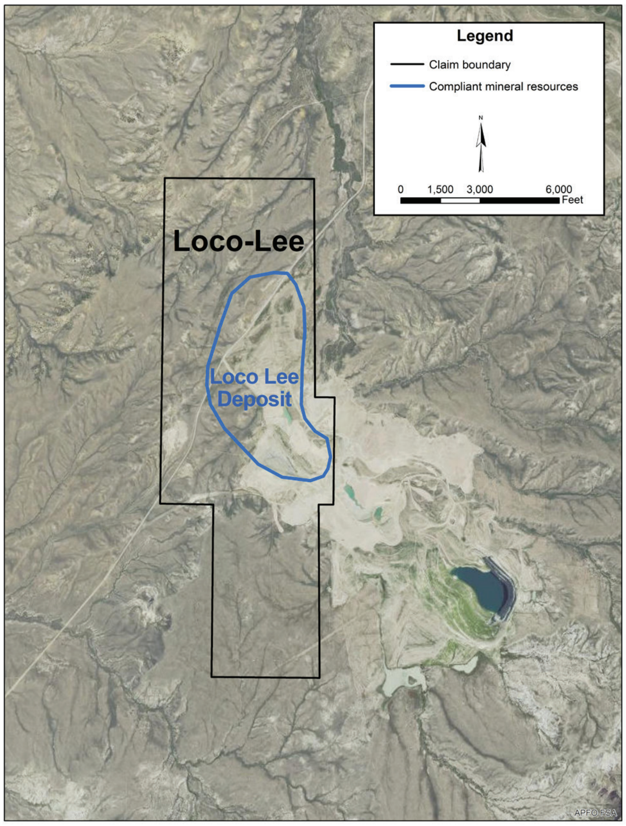

Figure 22. George Ver property (above right), SE1/4, T. 33 N., R. 91 E., modified from Nielsen and others (2013).

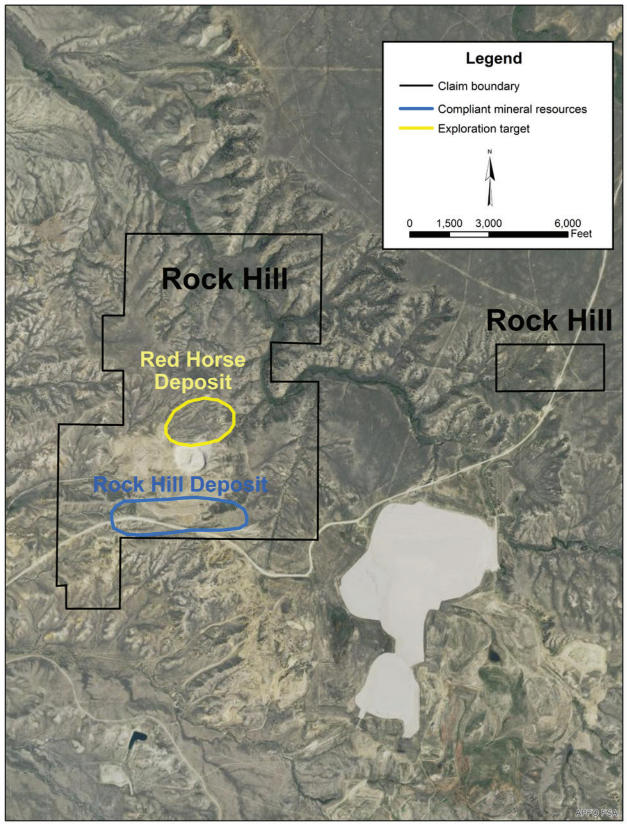

Figure 23. Rock Hill properties, N1/2, T. 33 N., R. 89 E., modified from Nielsen and others (2013).

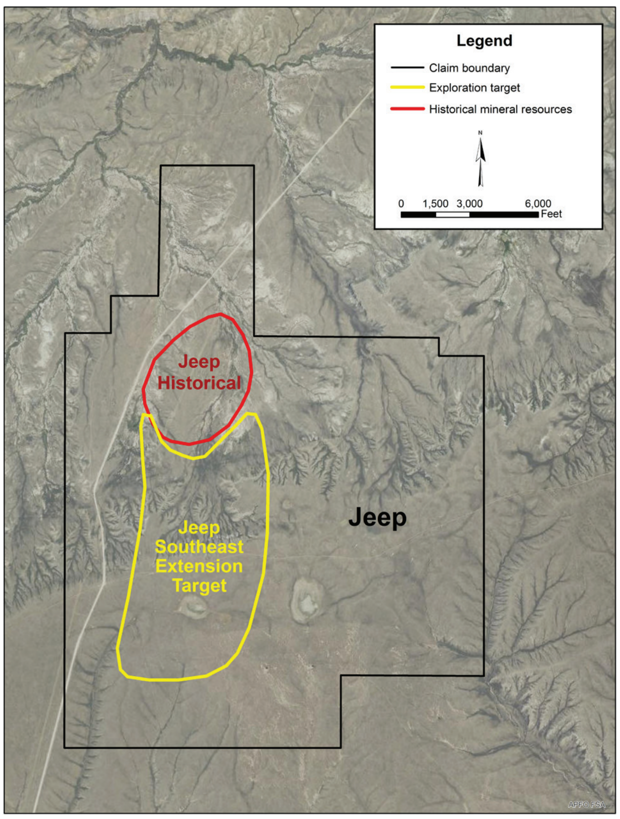

Figure 24. Jeep historical resource and exploration areas, N1/2 T. 31 N., R91 W., and S1/2 T. 32 N., R. 91 W., modified from Nielsen and others (2013).

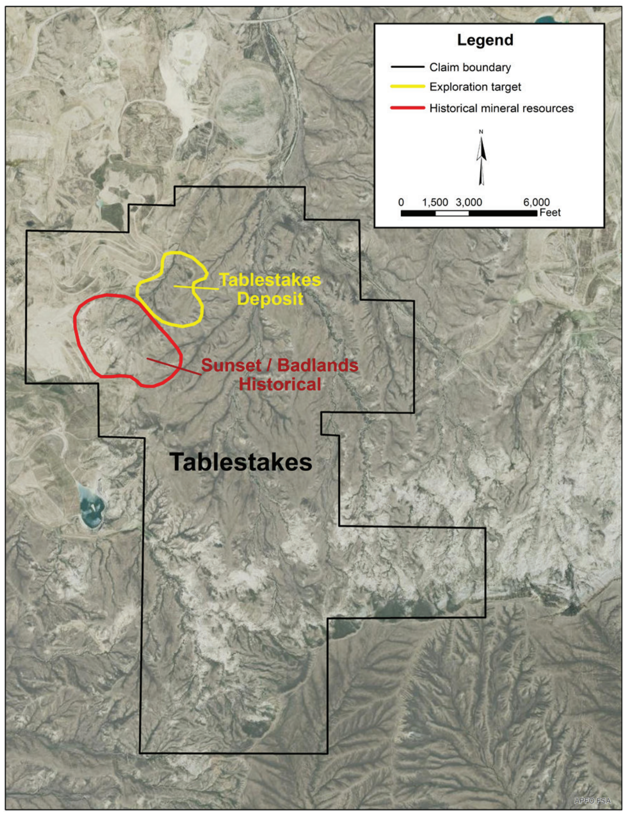

Figure 25. Tablestakes exploration (includes Amazon area) and historical resource areas, NW T. 32 N., R. 90 W., and SW T. 33 N., R. 90 W., modified from Nielsen and others (2013).

Table 3. Indicated and inferred mineral resource estimates, URZ Energy primary targets. Modified from Nielsen and others (2013).

Property name	Tons	Pounds eU_3O_8*	Grade eU_3O_8 (%)*
	Indicated resources**		
Day Loma	1,400,000	4,000,000	0.14
George Ver	900,000	1,400,000	0.08
Total	2,300,000	5,400,000	
	Inferred resources**		
Bullrush	900,000	900,000	0.05
Day Loma	600,000	1,200,000	0.10
George Ver	400,000	500,000	0.07
Loco-Lee	1,000,000	1,200,000	0.06
Rock Hill	1,100,000	1,700,000	0.08
Total	4,000,000	5,500,000	

Source: Nielsen and others (2013)

* eU_3O_8 = equivalent amount of U_3O_8 contained in resource

** based on minimum grade cut-off of 0.04% and minimum thickness of 1 ft

Table 4. Indicated and inferred mineral resource estimates, URZ Energy primary targets. Modified from Beahm (2017).

Property name	Tons	Pounds eU_3O_8*	Grade eU_3O_8 (%)**
	Indicated resources**		
Day Loma	1,342,000	2,948,000	0.110
George Ver	623,000	1,027,000	0.082
Loco-Lee	442,000	755,000	0.085
Totals	2,407,000	4,730,000	
	Inferred resources**		
Bullrush	310,000	401,000	0.05
Day Loma	136,000	271,000	0.10
George Ver	738,000	938,000	0.07
Loco-Lee	317,000	330,000	0.06
Rock Hill	824,000	589,000	0.08
Totals	2,325,000	2,529,000	

Source: Beahm (2017)

* eU_3O_8 = equivalent amount of U_3O_8 contained in resource

** based on minimum grade cut-off of 0.02% and minimum thickness of 2 ft

both were prepared by "Qualified Persons" as required for compliance with NI 43-101 standards.

The general locations of Cameco's mine units within their property boundaries in the Gas Hills district are also shown in figure 18. Cameco Corporation reports total measured, indicated, and inferred resource estimates on their website for the Peach deposit of approximately 7.62 million short tons of ore of varying grades, representing about 19.3 million pounds of equivalent U_3O_8 (table 5).

Nielsen (2013) cites mineral reserves and resources as reported on December 31, 2012, for Cameco's Gas Hills properties of approximately 25.9 million pounds (table 6). The reserves and resources listed in table 6 are not assigned to any particular group(s) of claims.

Exploration targets

There are several additional properties controlled by URZ Energy in the Gas Hills district, primarily in the western and central portions of the district, which have been explored and evaluated by previous mining companies. Figures 19–25 show the proximity of these explorations targets to the primary targets listed in table 4. Most of these additional targets are extensions of the primary targets and have not been adequately delineated through drilling and logging. The majority of estimates incorporated into these evaluations were calculated prior to 1990 (Nielsen and others, 2013); the properties would require additional exploration and verification to meet NI 43-101 standards for the classification of measured, indicated, or inferred resources. There are a number of reasons that such estimates do not qualify as NI 43-101 compliant, including but not limited to 1) insufficient chemical assays, 2) lack of "closed can" radiometric analyses, in which light is prevented from interfering with the counting of emissions from the radioactive elements of interest, and 3) lack of PFN (a technique that can provide an accurate measurement of uranium content by measuring neutrons emitted during fission of ^{235}U isotopes, eliminating the inaccuracies associated with disequilibrium) and gamma ray data. These areas include Andria, approximately 2 miles north of Day Loma; Amazon, Sunset, and Badlands, approximately 2 miles south of Bullrush; Frazier-Lemac, adjacent to George Ver; and Jeep, which includes an adjacent area referred to as Jeep SE, approximately 4 miles southeast of Day Loma (fig. 18). The historic resource estimates of these areas are presented in table 7.

A third group of exploration targets, also with limited drilling and assay data, exists in the western and central Gas Hills district, most of which are outlined in yellow in figures 19–25. Several of these deposits have undergone limited exploration drilling and chemical assaying but also do not meet the standards of NI 43-101 and are thus considered conceptual and not classified as resources. Further drilling, assaying, and verification could also delineate these deposits as mineral resources. Table 8 shows the ranges (low and high averages) of extensions of previously discussed primary production targets. Some data used for the ranges presented in table 8 are from within areas of known historical resources and are thus not depicted in yellow in figures 19–25.

South of Beaver Rim, the Puddle Springs Arkose Member of the Wind River Formation lies at approximately 550–1,200 ft below ground level (Nielsen and others, 2013). URZ Energy holds claims in four separate areas south of Beaver Rim. From southwest to northeast (fig. 18) they are West Diamond, East Diamond, South Black Mountain, and North Black Mountain. Exploration has consisted of several hundred drill holes in areas currently controlled by both URZ and Cameco.

Armstrong (1970) estimated that the Gas Hills district uranium deposits have the potential to produce

Table 5. Cameco resource estimates (2017).

Classification	Tonnes	Short tons*	Grade % U_3O_8	Pounds (eU_3O_8)**
Measured	687,200	757,501	0.11	1,700,000
Indicated	3,626,100	3,997,050	0.15	11,600,000
Inferred	3,307,500	3,645,857	0.08	6,000,000
Totals	7,620,800	8,400,408		19,300,000

Source: Cameco Corporation (2017)

* calculated from tonnes (metric tons) as reported by Cameco

** eU_3O_8 = equivalent amount of U_3O_8 contained in resource

Table 6. Cameco resource estimates as reported in Nielsen and others, 2013.

Classification	Tonnes	Short tons*	Grade (% U_3O_8)	Pounds (eU_3O_8)**
Probable reserve	999,200	1,101,418	0.11	2,400,000
Measured resource	1,964,200	2,165,138	0.08	3,400,000
Indicated resource	6,857,900	7,559,463	0.12	18,800,000
Inferred resource	861,500	949,631	0.07	1,300,000
Totals	10,682,800	11,775,650		25,900,000

Source: Nielsen and others (2013)

* Calculated from tonnes (metric tons) as reported by Nielsen and others, 2013

** eU_3O_8 = equivalent amount of U_3O_8 contained in resource

Table 7. Resource estimates of URZ exploration targets. Modified from Nielsen and others (2013).

Deposit name	Short tons	Pounds eU_3O_8*	Grade (% U_3O_8)
Amazon	285,000	366,000	0.06%
Andria	740,000	950,000	0.06%
Badlands	163,000	216,000	0.07%
Frazier-Lemac	697,000	1,522,000	0.11%
Jeep	297,000	463,000	0.08%
Sunset	1,395,000	1,813,000	0.06%
Totals	3,577,000	5,330,000	

Source: Nielsen and others (2013)

* eU_3O_8 = equivalent amount of U_3O_8 contained in resource

Table 8. Resource estimates of primary target extensions. Modified from Nielsen and others (2013).

	Pounds eU_3O_8*	
Deposit name	Low	High
Bullrush	500,000	1,400,000
Day Loma, NE Trend	200,000	1,100,000
Day Loma, SE Trend	200,000	1,800,000
George-Ver, Antelope	1,100,000	3,500,000
Loco-Lee	800,000	1,800,000
Tablestakes	300,000	1,700,000
Jeep, South Extension	200,000	1,100,000
Total Potential	3,300,000	12,400,000

Source: Nielsen and others (2013)

* eU_3O_8 = equivalent amount of U_3O_8 contained in resource

up to 200 million pounds of yellowcake, depending on favorable economic circumstances. By that measure, a little more than half of that figure has been extracted to date. Market conditions dictate exploration activity and ultimately production. The most recent surge in uranium mining project development in the United States resulted from a jump in prices from about $8 per pound in 2000 to $137 per pound just seven years later.

In 2017 owners and operators of nuclear power plants in the United States purchased 43 million pounds of U_3O_8, 40 million pounds (93 percent) of which came from five foreign countries: Canada, Australia, Russia, Kazakhstan, and Uzbekistan; 3 percent coming from domestic producers in Wyoming Nebraska, and Utah (U.S. Energy Information). The U.S. Department of Commerce (DOC) recently completed a report on its investigation on the effects of uranium imports, particularly from adversarial countries and their allies, on U.S. national security. That report was submitted to the White House on April 14, 2019. Uranium industry experts are optimistic that domestic production quotas will be increased resulting in rising prices.

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