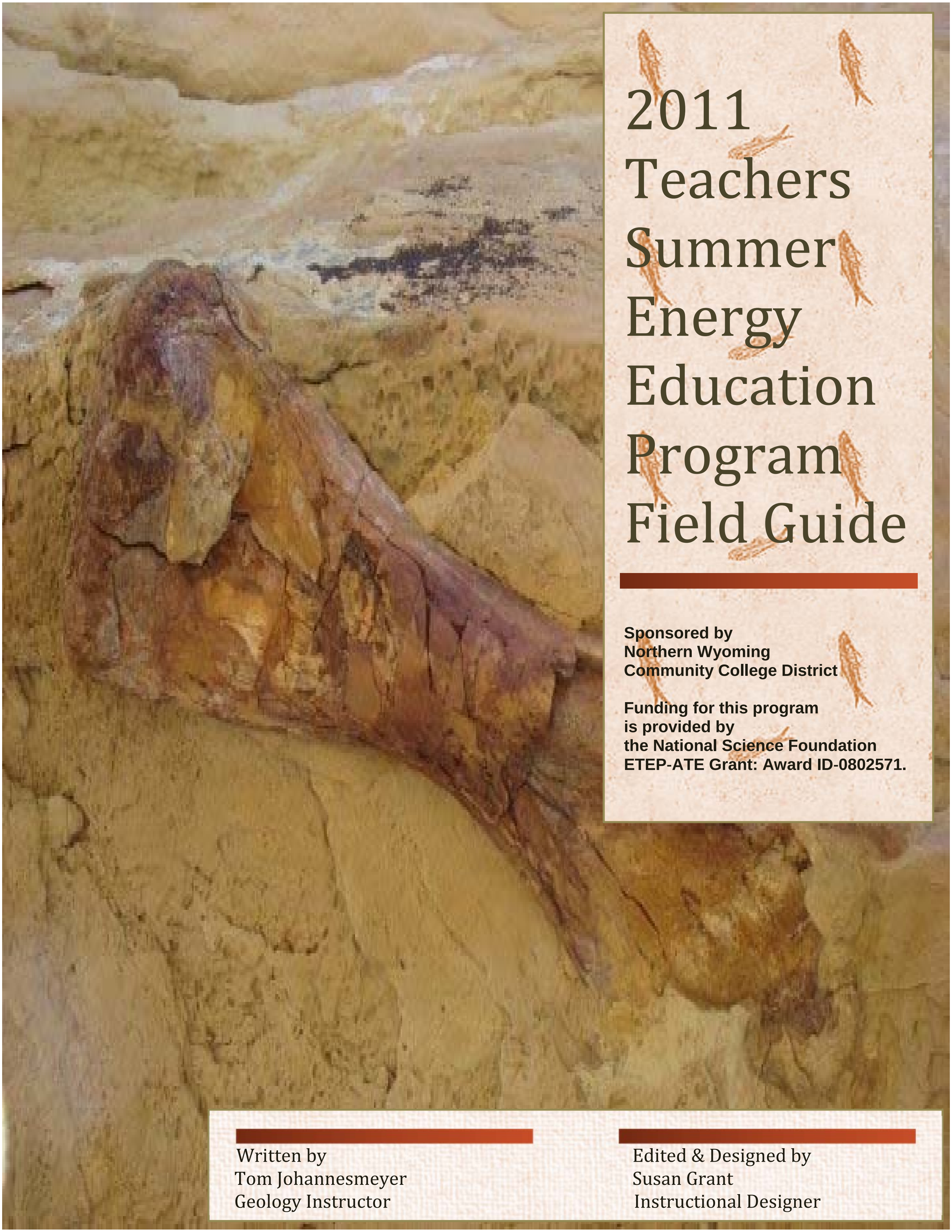

2011 Teachers Summer Energy Education Program Field Guide

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Written by
Tom Johannesmeyer
Geology Instructor

Edited & Designed by
Susan Grant
Instructional Designer

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Sheridan to Buffalo Roadside Geology

Bighorn Mountains and Powder River Basin

Sheridan, Wyoming is located on the extreme western margin of the Powder River Basin (PRB) and adjacent to the east flank of the Bighorn Mountains. Bighorn Mountains are a large basement-cored anticline structure that formed during the Laramide Orogeny that began in Late Cretaceous Period and culminated in the Early Eocene Epoch (Figure 1).

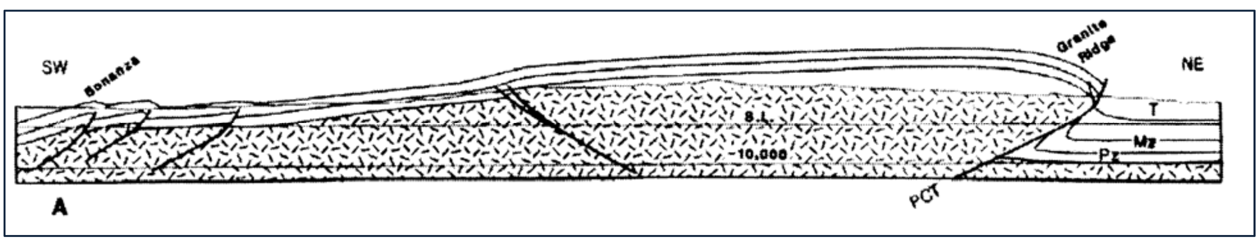


Figure 1: Structural cross section of the Bighorn Mountains, WY. Section line trends northeast to southwest from Story, WY to near Worland, WY (Stone, 2003).

The PRB is the sedimentary and asymmetric structural basin (give dimensions) that formed in response to the development of the Bighorn Mountain and Black Hills uplifts. Moving westward from Sheridan towards the Bighorn Mountain front, progressively older sedimentary formations are encountered (Figure 2).

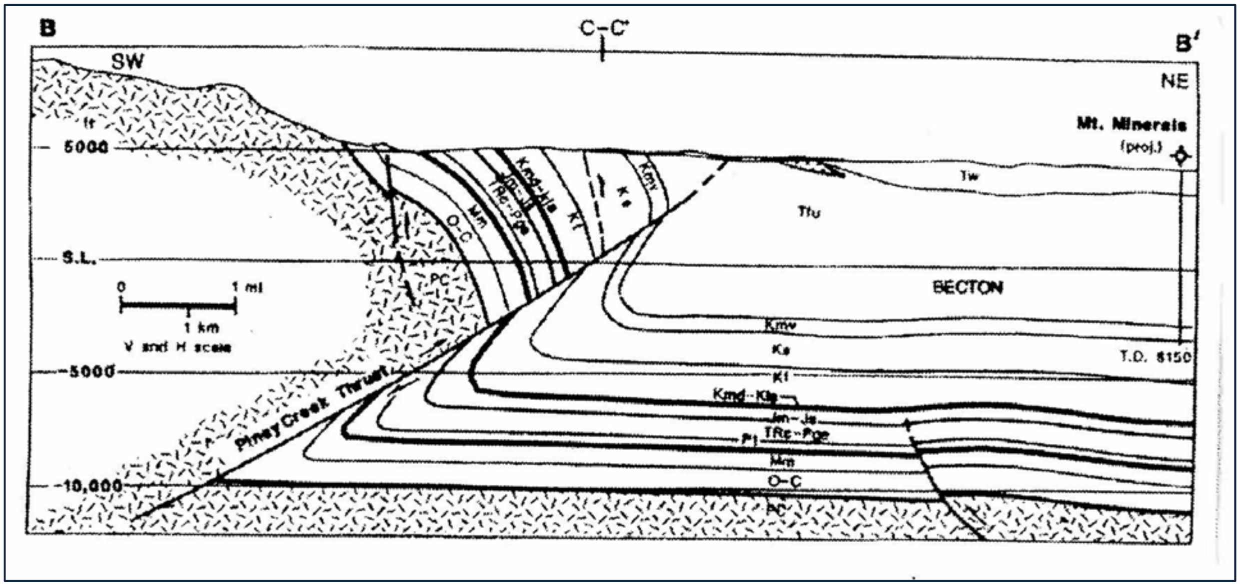


Figure 2: Detailed structural cross section of the eastern Bighorn Mountain front west of Sheridan, WY (Stone, 2003)

Sheridan sits on the contact between the Eocene Wasatch and Paleocene Fort Union formations which dominates surface outcrops from Sheridan to about half the distance to the Bighorn Mountain range front and eastward into the PRB. The Fort Union Formation overlies a complex sequence of Cretaceous formations which also outcrop poorly due to abundant shale and form the gently grass covered foot hills. Very near the range front, Jurassic Period sediments outcrop such as the dinosaur fossil-rich Morrison Formation. The abrupt break in slope at the range front is underlain by moderately east dipping Paleozoic sedimentary formations. The core of the range, which includes most of the high peaks, is largely composed of Archean granites and gneisses. The stratigraphy of the western Powder River Basin and eastern Bighorn Mountains is summarized in Figure 3.

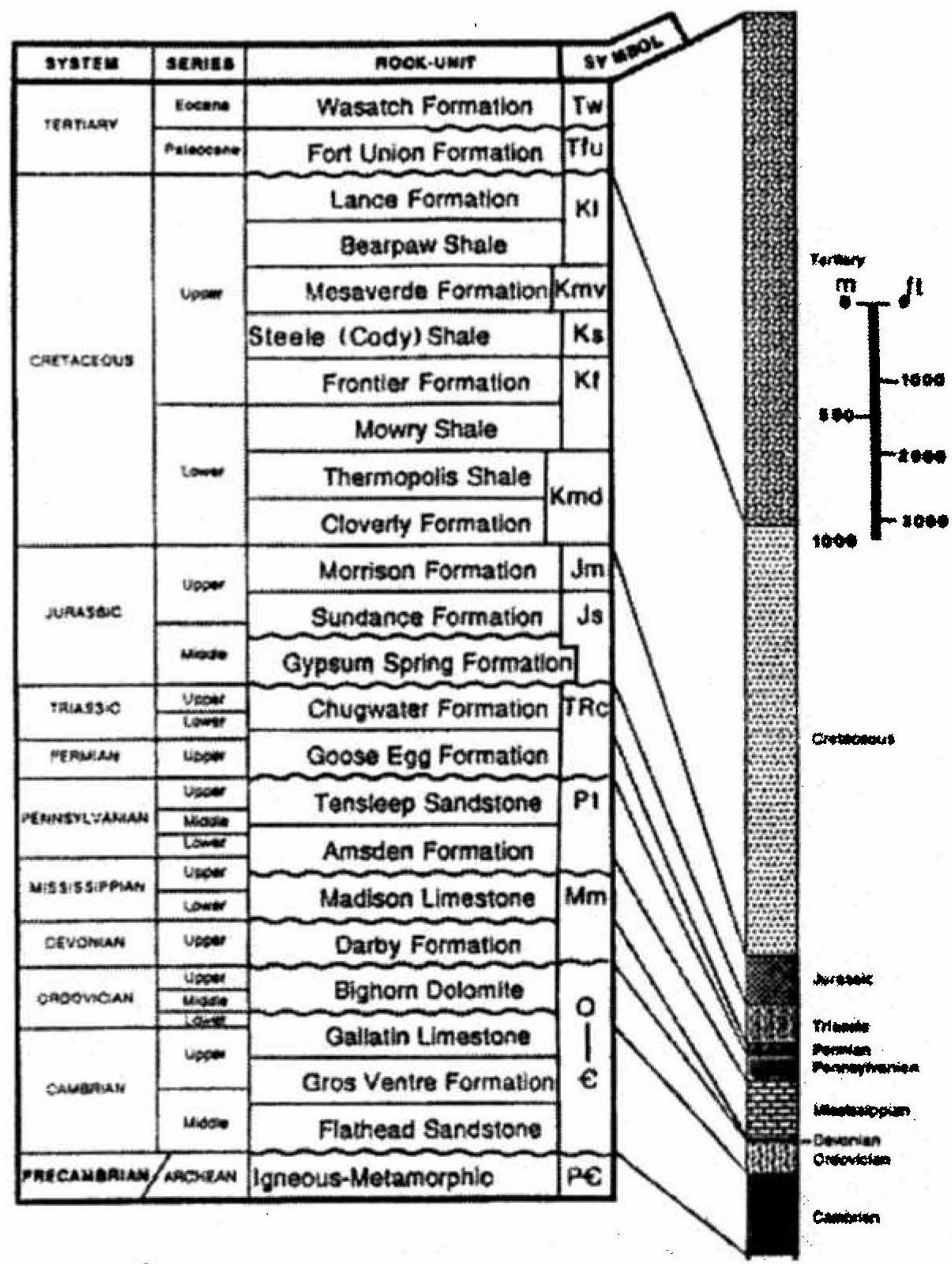


Figure 3: Stratigraphic column for the eastern Bighorn Mountain region illustrating the relative thickness of rock units (Stone, 2003)

The contact between the Eocene Wasatch formation and the underlying Paleocene Fort Union Formation is roughly coincides with Sheridan and runs parallel to the Bighorn Mountain trend. This contact is not characterized by a significant unconformity or change in lithology making locating this formation boundary in the field very difficult. So why is this formational bound chosen? In short, the Eocene Wasatch Formation, Paleocene Fort Union Formation, and Upper Cretaceous Lance Formation represent a conformable sequence of fluvial sandstone, siltstone, shale; lacustrine shale and limestone; and coal beds deposited from the Late Cretaceous Period to Eocene Epoch as the Powder River Basin developed in response to the Laramide Orogeny which uplifted the Bighorn Mountains on the western margin and the Black Hills on the eastern margin. Early workers separated these formations based on age, which is not consistent with the North American Stratigraphic Nomenclature. Boyd (1994) has suggested that this conformal sequence of sediments be named the Powder River Group representing the Upper Cretaceous to Early Eocene System in this part of Wyoming.

Wasatch Formation

As we travel south of Sheridan along Interstate 90 to Buffalo, WY, numerous outcrops of Eocene Wasatch Formation carbonaceous shale is exposed in highway cuts. In general, the Wasatch Formation dips to the east towards the Powder River Basin. The presence of abundant petrified wood fragments readily distinguishes this shale from similar Cretaceous carbonaceous shale and provides some of the evidence that this shale represents lacustrine (lake) deposits. This shale is also prone to sliding and slumping and numerous examples can be identified along this stretch of interstate highway.

Clinker in the Wasatch Formation

Reddish, erosion resistance clinker deposits cap numerous hills and buttes to the east. Clinker is a suite of contact metamorphic rocks that form as coal seams combust in the subsurface, baking shale, mudstone, siltstone, and sandstone to a natural brick. Coal seams may be ignited by either lightning strikes, prairie wild fires, or the heat of wetting and oxidation of pyrite and marcasite (a low temperature polymorph of pyrite). Some portions of clinker deposits show evidence of complete melting, giving the rock a vesicular texture (a Swiss cheese-like texture) that locals incorrectly refer to as 'scoria' (geologist reserve this term for highly vesiculated basalt). Clinker also occurs extensively in the underlying Fort Union Formation. Because of its availability and durability, clinker is often used as construction aggregate and landscaping rock within the Powder River Basin. A more extensive discussion on clinker may be found in Day 5 of this field trip guidebook.

Lake DeSmet

Lake DeSmet is a natural lake that has been artificially enhanced capacity via an earthen dam. Surface exposures consist of shale, siltstone, sandstone, and coal beds of the Eocene Wasatch Formation. Locally spectacular occurrences of petrified longs are common in these deposits and are exposed in shoreline escarpments. While most of the coal mined in the Powder River Basin is produced from the Tongue River Member of the Fort Union Formation, subsurface borings indicate a significant coal reserves lay beneath the Lake DeSmet region – the Lake DeSmet coal zone of the Wasatch Formation. Coal-bed methane development has largely waned here, with some wells still producing. A few old well casing strings are exposed as 30-40' 10-12" pipes protruding from the middle of a clinker open-pit near the north end of the lake.

Buffalo to Tensleep Roadside Geology

The field trip route follows U.S. highway 16 over the Bighorn Mountains to Tensleep. As the highway climbs to the base of the Bighorn Mountains along the Clear Creek valley outcrops of syntectonic conglomerate of the Kingsbury Member of Wasatch Formation appear. These Eocene gravels represent the remains of a large alluvial fan complex that was shed in response to erosion that ensued following the Laramide uplift of the Bighorn Mountains. A large turnout to the north, approximately 7.7 miles from downtown Buffalo, exposes Paleozoic sedimentary rocks that are in fault contact with the Kingsbury Member of the Wasatch Formation a few hundred yards further down the road, the Cambrian Flathead Formation rests upon Archean igneous and metamorphic rock which represent the structural core of the Bighorn Mountains.

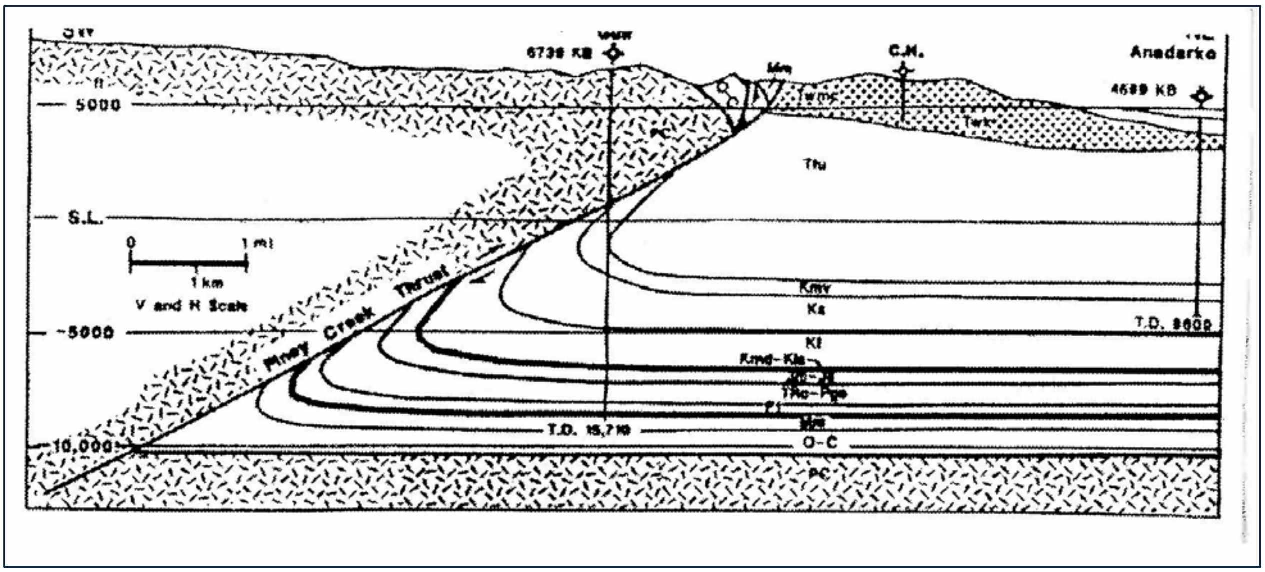


Figure 4: Detailed structural cross section of the eastern Bighorn Mountain front west of Buffalo, WY (Stone, 2003)

For the next thirty-five miles, the highway traverses the Bighorn Mountains over Archean gneiss and granite gneiss. At this point the highway begins to descend into Tensleep Canyon on the west slope of the Bighorn Mountains. Also, look for large boulders in road cuts that indicate the large terminal moraine complex at the head of Tensleep Canyon.

Tensleep Canyon

Approximately forty-eight miles from Buffalo, U.S. 16 descends into the spectacular Tensleep Canyon. Prominent cliff-forming rock units exposed include, in order of appearance, the Ordovician Bighorn Formation, Mississippian Madison Formation, and Pennsylvanian Tensleep Formation. These Paleozoic formations are discussed in more detail in the Wind River Canyon section of this guidebook on Day 1.

Tensleep to Thermopolis Roadside Geology

The twenty-seven miles from Tensleep to Worland crosses over generally southwest dipping Triassic to Eocene bedrock of the southeast corner of the Bighorn Basin. The Bighorn Basin is a Laramide sedimentary and structural basin bounded on the west by the Absaroka Mountains, to the east by the Bighorn Mountains, and to the south by the Owl Creek Mountains – all Laramide uplifts.

Cottonwood Creek Oil Field

Located about midway between Tensleep and Worland, the Cottonwood Creek oil field, discovered in 1953, produces from the Ervay Limestone Member of the Permian Phosphoria Formation which is encountered at depths ranging from 5,000 to just over 10,000 feet. The areal extent of the field is about 7 by 4 miles. Cumulative production was more than 44.5 million barrels in 1979 with original oil in place estimated at 182 million barrels (Herrod, 1980). 2010 production was 239,000 barrels of oil and 451 MMCF of natural gas (Wyoming Oil and Gas Conservation Commission, 2011).

Bighorn Hot Springs, Thermopolis, Wyoming

Thermopolis is home to one of Wyoming's most famous hot spring - Bighorn Hot Springs. The spring is the central attraction of Hot Springs State Park which features two commercial hot springs, one public bath house, and numerous natural springs and travertine deposits. With a discharge of roughly 18,000 gallons of 135^{o} F water per day, Bighorn Hot Springs ranks as one of the largest hot springs on Earth.

Figure 5 illustrates the origin of these hot springs. The town of Thermopolis and the hot springs rests on the edge of the northwest-southeast trending Thermopolis anticline and thrust fault. The core of the fold is well marked by distinctive red shale and sandstone of the Triassic Chugwater Formation. Fractures associated with the thrust fault and anticline provides a surface conduit for deep groundwater. The deep groundwater is recharged by precipitation in the Owl Creek Mountains south of Thermopolis where it then travels north into the subsurface through permeable limestone and dolostone formations before encountering the Thermopolis thrust fault and fractures associated with the Thermopolis anticline. This now heated, deep groundwater is forced upward by the large hydraulic head to produce an artesian hot spring. As the discharged waters cool, they precipitate dissolved calcium carbonate to form travertine terraces.

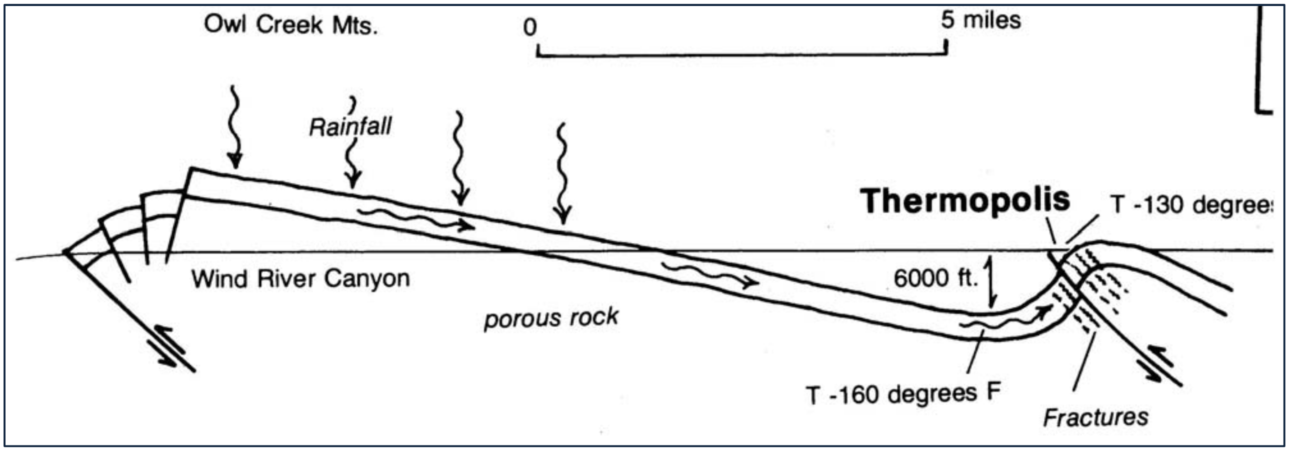


Figure 5: Origin of Big Horn Hot Springs, Thermopolis, WY (Lageson and Spearing, 1988)

Thermopolis to Riverton Roadside Geology

The field trip route from Thermopolis to Riverton leaves the Bighorn Basin, crosses the Laramide Owl Creek Mountains through the Wind River canyon, then emerges into the Wind River Basin.

Wind River Canyon

Traveling south of Thermopolis, the field trip route follows the spectacular Wind River Canyon. The Wind River Canyon has been carved by the Wind River (the name of the river changes to the Bighorn River after the Wedding of the Waters south of Thermopolis) as is flows northward through the Laramide Owl Creek Mountains. From Thermopolis to the head of the Wind River Canyon, progressively older strata from Cretaceous to Archean are exposed at highway level due to the northward structural dip of 4^{o} to 10^{o} (Figure 6) of the strata on the hanging wall of the Owl Creek Mountains uplift.

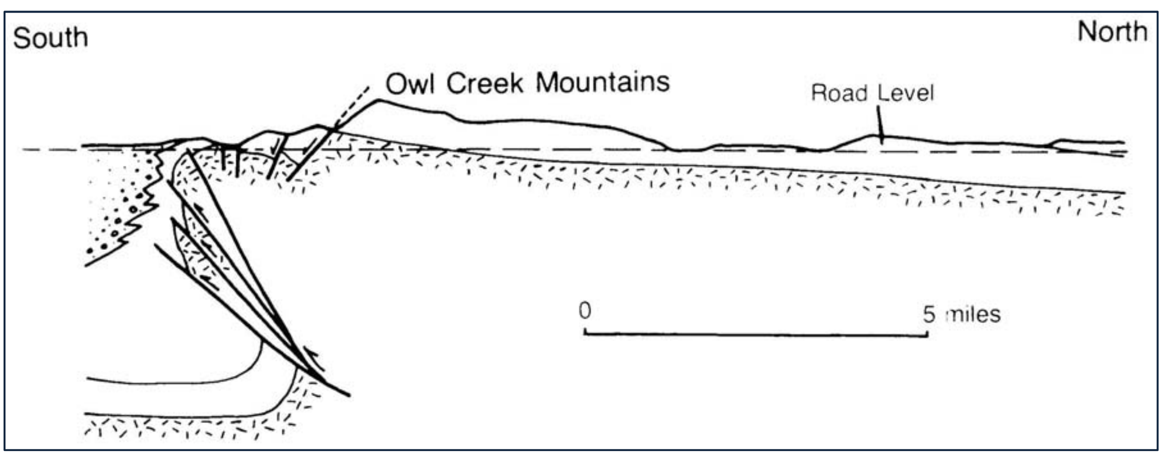


Figure 6: North-south structural cross section of Owl Creek Mountains. Section line runs from Thermopolis, WY to Boysen Reservoir at the south end of the Wind River Canyon (Lageson and Spearing, 1988)

Geomorphic Evolution of the Wind River Canyon

The Wind Rivers' course through the Wind River Canyon is an excellent example of the principle of stream superposition first articulated by John Wesley Powell in 1888. The Owl Creek Mountain uplift occurred during the Laramide Orogeny (~ 80 - 35 Ma) but was subsequently eroded during the Eocene to Oligocene epochs (56 – 23 Ma) and the sediments derived were deposited in adjacent basins such as the Wind River, Bighorn, and Powder River basins. As the mountains eroded and the basin deposits accumulated, a subdued topography again developed across Wyoming. At this time, the ancient Wind River developed its course northward across the buried Owl Creek uplift.

However, during the Miocene to Pleistocene epochs (23 Ma to 10 ka), broad regional uplift associated with the Yellowstone Hot Spot Track and a wetter climate resulted in increased stream down-cutting. The Wind River down-cutting has been able to keep up with uplift rates so that the course may be maintained despite the underlying structure. Dating of Horsethief Cave in the Madison Limestone located in Bighorn County, Wyoming, give down-cutting rates for the Bighorn River of 0.35 mm/yr. Similar rates would apply to the Wind River Canyon should karst features in the Madison be of similar age there.

Mesozoic Formations

Cretaceous formations are not readily seen from the highway; although, a good section of Jurassic to Triassic formations are moderately well exposed. The Jurassic system here includes the Gypsum Springs, Sundance and Morrison Formations and the Triassic system includes the Dinwoody Formation and Chugwater Group (which includes the Red Peak Formation, Crow Mountain Sandstone, and Popo Agie Formation). All these strata dip northward towards an east-west striking fault which defines the northern boundary of the Owl Creek Mountains structural block and provides the subsurface conduit along which thermal waters travel to produce Bighorn Hot Springs at Thermopolis.

Paleozoic Formations of the Wind River Canyon

Permian Phosphoria and Park City Formations: these important oil and gas producing formations in Wyoming outcrop as the upper most strata of the canyon rim. Collectively these formations produce a cliff- and slope-forming sequence with two prominent cliff forming units. The upper cliff-forming unit is the 55-ft Ervay Limestone Member of the Phosphoria Formation which produces a spectacular dip slope on the north flank of the Owl Creek Mountains. This unit consists of light gray dolomitic limestone and dolomite. Upper beds of oolitic and stromatolitic beds indicate a shallowing-upward carbonate shelf sequence. Below the Ervay Limestone is a largely slope-forming sequence consisting of phosphatic shale, chert, and limestone of the Park City and Phosphoria Formation. The lower cliff-forming unit is a 40 ft thick sandy dolomite of the Lower Permian Grandeur Member of the Park City Formation which sits upon a disconformity eroded into the underlying Tensleep Formation. Locally, up to 10 ft of erosional relief occurs on this surface. This yellowish gray, sandy and cherty dolomite contains broken shells, fragmented chert, and sand derived from the underlying Tensleep formation and is interpreted as storm surge deposits within intertidal to supratidal zones.

Tensleep Formation

Deposited in the Middle Pennsylvannian Period, The Tensleep Formation (also referred to as Tensleep Sandstone) consists of two dominant members comprising a total thickness of 195 to 290 ft. The upper cliff-forming member consists of yellowish gray, cross-bedded sandstone deposited in eolian dunes and interdune environments transported from north to south. This sandstone member is also an important oil and gas reservoir in Wyoming. The lower member is characterized by thin to medium beds of silty to sandy dolomite, dolomitic sandstone, and greenish gray mudstone deposited on a shallow marine shelf.

Amsden Formation

The Upper Mississippian to Middle Pennsylvanian Amsden Formation forms the slopes between the overlying cliffs of Tensleep Sandstone and the underlying cliffs of Madison Limestone. From the top of the formation, three distinct members can be recognized in the field: Ranchester Limestone, Horseshoe Shale, and Darwin Sandstone. The Ranchester Limestone Member is not as well developed in the Wind River canyon and consists of thin limestone beds on top of the Horseshoe Shale. The Horseshoe Shale is characterized by a 100 to 200 ft thick section of red to orange red mudstone with a conglomeratic base. This member has been interpreted as terra rosa re-sedimented during the transgression of the Pennsylvannian sea. The upper member of the Amsden Formation, the Darwin Sandstone, is only present locally. This red to orange cross-bedded sandstone was deposited as eolian dunes within a sabkha complex resulted from a marine regression that followed the deposition of the underlying Madison Formation.

Madison Limestone

The Madison Limestone is a 440- to 550-ft thick sequence of limestone, dolomitic limestone and dolomite beds that produces many of the most prominent cliffs in the Wind River Canyon. Deposited during the Mississippian marine transgression, basal deep water deposits are overlain by shallow-water deposits as carbonate sediments prograded across the shelf. The upper most Bull Ridge Member contains evidence of shallow water environments with oolitic and stromatolitic dolomitic limestone beds and evidence of dissolved evaporate beds indicative of intertidal to supratidal environments. Karst features are also common in the upper members of the Madison Formation.

Bighorn Dolomite

Deposited in a regionally extensive tropical marine shelf environment, the 85 to 140 foot thick Middle to Late Ordovician Bighorn Dolomite forms the lower most prominent carbonate cliffs in the Wind River Canyon. The lowest member, the massive Steamboat Point Member, is mottled light to medium gray and a medium to coarse grained crystalline dolostone with locally abundant chert nodules. Incomplete dolomitization results in variable weathering that produces innumerable pockets and pits on cliff exposures. Also, cyclic bedding on a scale of ~1-3 feet is visible from a distance and has been interpreted as the result of ~100 to 400 ka glacial-induced sea level fluctuations.

Gallatin Formation

With a total thickness up to 450 ft, the Late Cambrian Gallatin Formation consists of medium gray to greenish gray, thin-bedded to laminated limestone with interbeds of clayey limestone and silty calcareous claystone. A unique and enigmatic rock type, the so-called 'flat-pebble conglomerate', is the characteristic rock type of the Gallatin Formation. These flat-pebble conglomerates are interpreted as rip-up clast deposits produced by storms that agitated the generally low energy, shallow water marine environments characteristic of this period.

Gros Ventre Formation

A major slope-forming unit, the Middle to Late Cambrian Gros Ventre Formation dominantly consists of medium to dark greenish gray micaceous and glauconitic mudstone. Clayey and silty sandstone beds occur in the lower portion of the formation, while calcareous mudstone and clayey limestone is commonly in the upper portion grading into the overlying Gallatin formation. Evidence for shallow water deposition of the Gros Ventre Formation includes ripples and horizontal burrows and tracks (many from trilobites) on bedding surfaces, and the presence of flaser bedding.

Flathead Sandstone

The Middle Cambrian Flathead Sandstone marks the base of the Paleozoic stratigraphic section in the Wind River Canyon. The dominant and characteristic rock type is a yellowish gray to pale orange arkosic and micaceous quartz arenite (sandstone). This unit is a classic example of a lower foreshore to nearshore subtidal sandstone deposited as the Cambrian sea transgressed eastward onto the continental shelf producing a time-transgressive unit. Siltstone is also common as are glauconite grains.

The base of the Flathead Sandstone is marked by The Great Unconformity. This unconformity, or erosional surface, represents a gap in the geologic record of over 2 billion years. During this time, weathering and erosion produced a nearly flat surface cut into the underlying Precambrian rocks that form the basement rock of the North American continent. Regional differences in the thickness of the basal Flathead Formation beds indicate that this erosional surface was a gently undulating plain.

Archean Metamorphic and Igneous Rocks

These Precambrian rocks represent the basement rock of Wyoming and are among the oldest rocks in Wyoming and North America. Darker rocks are black hornblende amphibolite and quartz biotite schist. Formed at about 2,900 Ma and metamorphosed around 2,750 Ma, this sequence was likely originally a series of medium to fine grained shale, siltstone, and sandstone and basalt and basaltic andesite flows and/or dikes and sills. Light colored rocks are pinkish gray to white quartz monzonite intrusions some of which are pegmatitic.

Boysen Area Structural Complex
The southern end of the Wind River Canyon occurs in a zone known as the Boysen Area Structural Complex (Figure 7). The master fault, the South Owl Creek Mountains fault, dips to the north and is a Laramide structure that thrusts Precambrian and younger rocks southward over the deep part of the Wind River Basin resulting in up to 33,000 feet of structural relief. Subsequent extensional collapse of the lip of the hanging wall block overriding the South Owl Creek Mountains fault0 produced a zone of high angle normal faults, and associated grabens, the largest of which is the east-west trending Boysen fault. The highway crosses the Boysen fault, with its 50° to 70° south dip, at the beginning of the narrow part of the canyon (milepost 116.1). About 2000 to 2500 feet of stratigraphic displacement across the Boysen fault results in the Cambrian formations being down-dropped back to the highway level. Also, large blocks of Paleozoic limestone and dolostone have slid downhill along very large, low angle detachment faults.

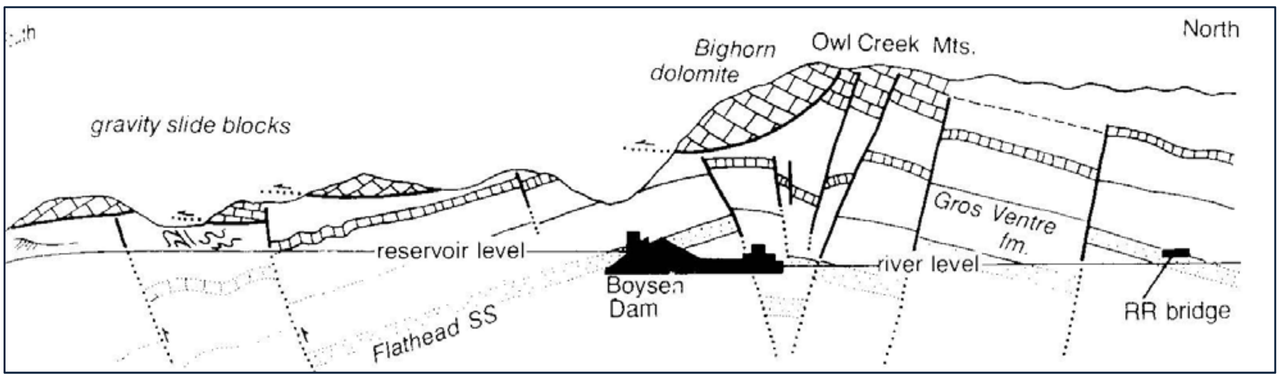


Figure 7: North-south structural cross section of the Boysen Area Structural Complex at the head of the Wind River Canyon (Lageson and Spearing, 1988)

Boysen Dam and Reservoir
Blocking the Wind River as it enters the Wind River Canyon, the Boysen earth-fill dam and reservoir was built between 1947 and 1952 and named for Asmus Boysen who built a dam near the present site in 1908 on land leased from Arapaho and Shoshone Tribe. The dam and most of current reservoir are on the Wind River Indian Reservation. Diversion of a major rail line resulted in construction of 1 1/3 mile railroad tunnel beneath the dam and a portion of the reservoir.

Wind River Basin
Emerging from the Wind River Canyon and the Boysen Area Structural Complex, the highway crosses into the Wind River Basin. The Wind River Basin is a deep structural basin bounded by uplifts produced during the Laramide Orogeny: the Wind River Range to the west, Owl Creek Mountains to the north, Granite Range to the south and Casper Arch to the east (Figure 8 and the cross section on the Geologic Highway Map of Wyoming).

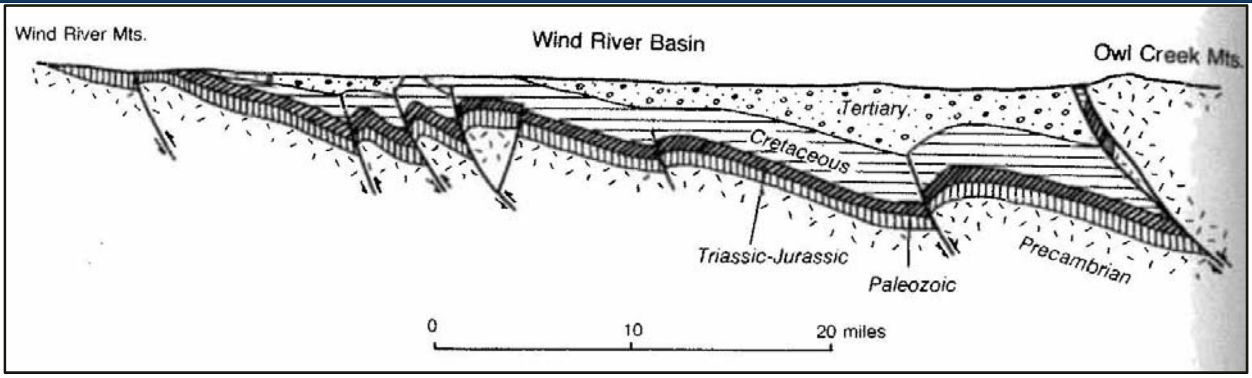


Figure 8: Northeast-southwest structural cross section of the Wind River Basin (Lageson and Spearing, 1988)

The basin contains about 10,000-12,000 feet of Paleozoic and Mesozoic strata which were tilted and deformed during Laramide orogeny. During the Laramide orogeny, about 18,000 feet of fluvial and lacustrine sediments where deposited unconformably upon previous Paleozoic and Mesozoic strata. About 8,000 feet of post-Eocene sediments where then deposited before late Tertiary uplift resulted in renewed down-cutting and terrace/pediment development.

Between the head of the canyon and Shoshoni, the highway crosses terraces and gravel-veneered pediment surfaces established on the lower Eocene Wind River Formation. Eocene rocks were deposited in braided stream and lacustrine environments with the sediment being derived from the erosion of the Owl Creek Mountains and Wind River uplifts.

Oil and Gas in the Wind River Basin

The first oil strike within the basin in 1884 resulted in the first commercial oil production in Wyoming. Now over sixty oil and gas fields tapping numerous Paleozoic and Mesozoic formations are known within the basin. Notable reservoir formations include the Cretaceous Muddy and Frontier Formations, the Permian Phosphoria Formation and the Pennsylvanian Tensleep Sandstone.

Most fields are structural traps, such as the Dallas Dome where oil was first discovered in the basin. These structural traps include numerous domes and anticlines buried beneath Eocene and younger sediments (Figure 8 and the cross section on the Wyoming Geologic Highway Map).

Shoshoni to Riverton Roadside Geology

From Shoshoni to Riverton the highway passes over the flat valley floor of the Wind River Basin cut into Lower Eocene Wind River Formation. Almost half the way to Riverton the highway drops onto upper terraces of the Wind River and the highway follows the Wind River valley to Riverton.

Day 1 Energy Industry Site Visit - Gas Hills Uranium District Tour

Background Information for Gas Hills Uranium District Tour

Host: Strathmore Minerals Corporation, Terrence Osier, Senior Geologist
Location: The Gas Hills Uranium District is located approximately 45 miles east-southeast of Riverton. Access is via Wyoming State Highway 139.

Wyoming's Uranium Reserves

Table 1 summarizes the U.S. Energy Information Administration's (EIA) year-end 2008 estimates of U.S. uranium reserves (U.S. EIA, 2010). Wyoming has the largest recoverable uranium reserves in the U.S. Total U.S. recoverable uranium reserves represent about 4-5% of global uranium reserves. Global uranium reserves by country are summarized in Table 2 (World Nuclear Association, 2010).

TABLE 1 – U.S. Uranium Reserves by State (2008)

State	$50/lb			$100/lb		
	Ore (million tons)	Grade[a] (%)	U_3O_8 (million lbs)	Ore (million tons)	Grade[a] (%)	U_3O_8 (million lbs)
Wyoming	145	0.076%	220	398	0.056%	446
New Mexico	64	0.140%	179	186	0.105%	390
Arizona, Colorado, Utah	22	0.145%	63	117	0.084%	198
Texas	15	0.089%	27	32	0.062%	40
Other[b]	28	0.090%	50	95	0.081%	154
Total	275	0.098%	539	828	0.074%	1,227

[a] Average percent U_3O_8 per ton of ore.
[b] Includes Alaska, California, Idaho, Montana, Nebraska, Nevada, North Dakota, Oregon, South Dakota, Virginia and Washington.

Notes: Uranium reserves that could be recovered as a byproduct of phosphate and copper mining are not included in this table. Reserves values in forward-cost categories are cumulative; that is, the quantity at $100 per pound U_3O_8 includes all reserves available up to and including that cost. Totals may not equal sum of components because of independent rounding. See EIA Glossary for definition of reserves. "Reserves," as reported here, do not necessarily imply compliance with U.S. or Canadian government definitions for purposes of investment disclosure.

Sources: Estimated by Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, based on company reports, industry conferences, and U.S. Department of Energy, Grand Junction Office, files.

TABLE 2 – 2009 Global Uranium Recoverable Reserves by Country		
	tonnes U	percentage of world
Australia	1,673,000	31%
Kazakhstan	651,000	12%
Canada	485,000	9%
Russia	480,000	9%
South Africa	295,000	5%
Namibia	284,000	5%
Brazil	279,000	5%
Niger	272,000	5%
USA	207,000	4%
China	171,000	3%
Jordan	112,000	2%
Uzbekistan	111,000	2%
Ukraine	105,000	2%
India	80,000	1.5%
Mongolia	49,000	1%
other	150,000	3%
World total	**5,404,000**	

History of Uranium Mining in the Gas Hills Uranium District

Uranium was first discovered in the Gas Hills in September 1953 by Neil McNeice, a.k.a. Lucky Mc, and within a year mining commenced and most of the area was staked (Anderson, 1969). Open pit mining was the dominant mining method due to the shallow occurrences of the uranium ores, but a few underground mines were developed. Historic production exceeded 100 million pounds of U_3O_8 making the Gas Hills the second largest uranium district in the United States (Strathmore website). The last uranium mining cycle ended in 1989.

Current Permitting and Exploration Efforts in the Gas Hills Uranium District

Strathmore Minerals Corporation (TSX: STM)

STM is the dominant land holder in the Gas Hills Uranium district with over 34,000 acres of minerals claimed (Figure 9).

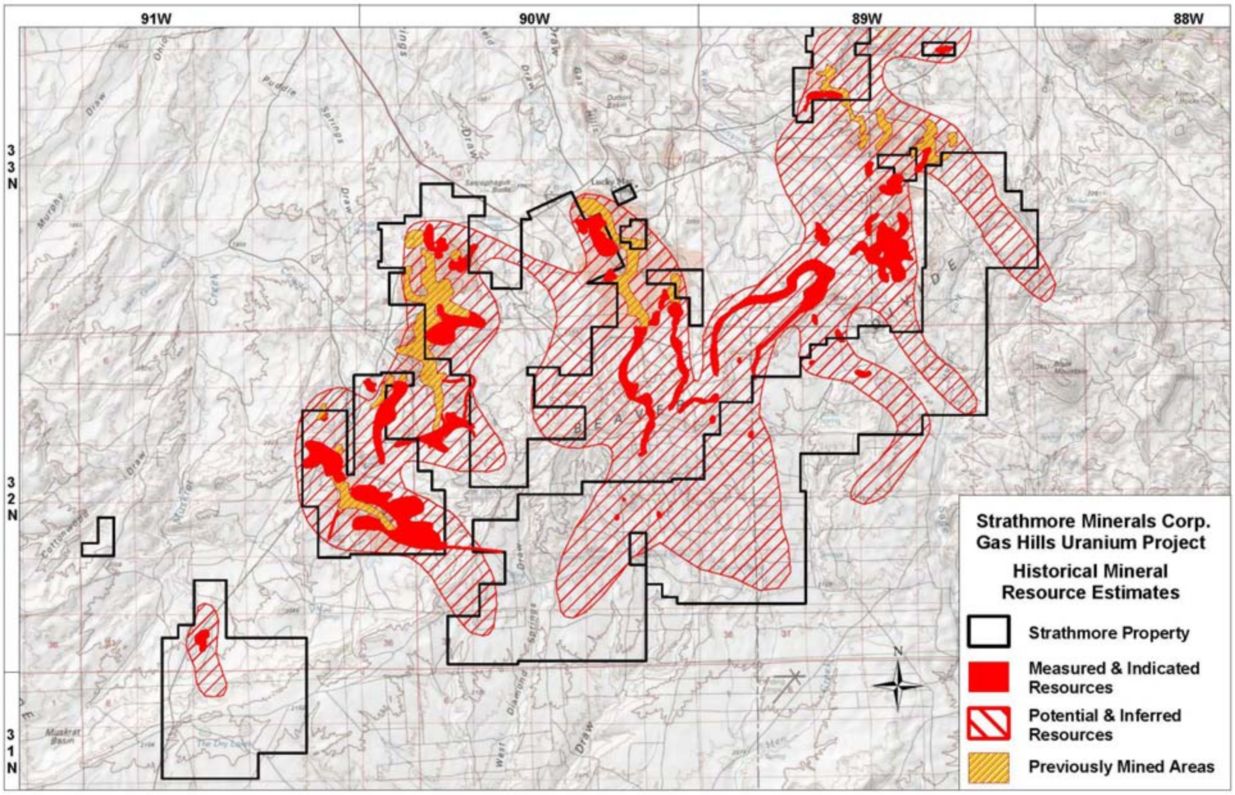


Figure 9: Map of Gas Hills Uranium District (Snow, 2011)

STM reports that these claims collectively contain approximately 17 million pounds of U_3O_8 measured and indicated from historical data. Ongoing exploration along Beaver Rim is likely to significantly expand reserves by about 20 million pounds of U_3O_8 bringing Strathmore's Gas Hills reserves to over 30 million pounds of U_3O_8. STM permitting efforts are focused on the George-Ver deposit, a historic open-pit mine, with mine permit application targeted for submittal by April 2011. In the fall of 2010, STM conducted confirmation, expansion, and pit delineation drilling, monitor well installation, and core sampling for metallurgical testing at George Ver, Day Loma and Loco-Lee properties. Geotechnical drilling and monitor well installation was also completed at the Sagebrush-Tablestakes site which is in evaluation as a uranium recovery facility. Acquisition of data libraries in 2010 has enabled STM to continue to expand its permitting activities. In addition to continued baseline permitting activities at other Gas Hills properties, STM is completing NI-43-101 compliant resource calculations for Georg-Ver, Day Loma and Loco-Lee deposits.

Mine permitting is project to be completed by mid-2012 followed by mine construction, with first production to occur in 2014. A summary of STM's Gas Hills properties with ore grade, mining method, total resources, and proposed sequence of development is summarized in Table 3.

Property	Resource	Grade	lbs. U3O8	Method
George-Ver (1) Bull Rush (2) Loco Lee (6)	Historical	0.069%	8.4 million	Open Pit
Frazier Lamac (4)	Historical	0.11%	1.5 million	Open Pit
Day Loma (3)	Historical	0.21%	1.9 million	Open Pit / ISR / Underground
Andria (5)	Historical	0.06%	.95 million	Open Pit
Rock Hill (7)	Historical	0.05 %	.90 million	Open Pit

Table 3: Summary of Strathmore Minerals Gas Hills Uranium District Proposed Projects (Strathmore Minerals Corp., 2011)

Cameco Resources (TSX: CCO; NYSE: CCJ)

Cameco (an acronym for Canadian Mining and Energy Corporation) is the world's largest publically traded uranium mining company and second largest producer of uranium accounting for about one-sixth of global uranium production. Cameco's Smith Ranch-Highland *In-Situ* Recovery (ISR) mine and plant north of Glenrock, Wyoming in the Powder River Basin (Day 3 energy industry site visit) is the largest uranium production facility in the United States. The company produces about 2 million pounds of yellowcake (processed uranium) per year from its U.S. properties which includes another facility at Crow Butte, Nebraska.

Cameco's holdings in the Gas Hills comprise about 8,500 acres of minerals claimed with over 90% on federal land managed by the Bureau of Land Management (BLM). Five ISR mine units are planned (figure 10) and permitting and exploration activity are ongoing.

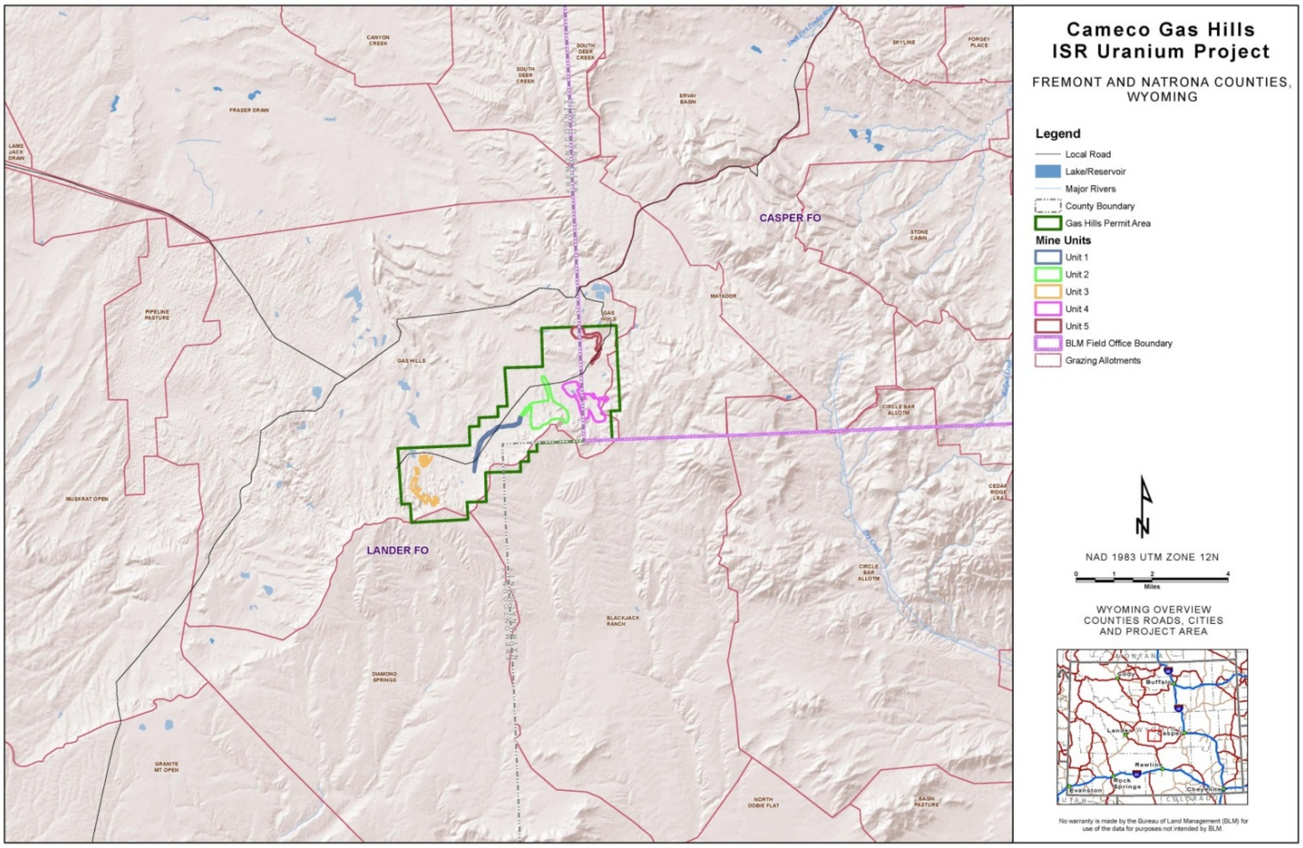


Figure 10: Map of Cameco's Gas Hills ISR Uranium Project. Compare with figure 9. (BLM, 2010)

Mine activity is projected to begin in 2014 with Cameco's Gas Hills production estimated to be up to 2.5 million pounds of U_3O_8 per year by 2018. This will double Cameco's U.S. uranium production. Probable reserves are estimated at 19 million pounds of U_3O_8 at an average grade of 0.13 % U_3O_8. Mine life is estimated at 20 years with 60 – 70 employees required to operate the facility. The Gas Hills properties will be operated as a satellite facility to the Smith Ranch-Highland mine and plant where the ore will be processed to produce yellowcake.

Geologic Setting of the Gas Hills Uranium District

The Gas Hills Uranium District sits at the south central margin of the Wind River Basin and against the northern margin of the Granite Mountains (also called the Sweetgrass Hills). The Eocene Wind River Formation (400 to 800 ft. thick) and Wagon Bed Formation (300 to 700 ft. thick) unconformably overly folded and faulted Mesozoic and Paleozoic sedimentary rocks (Armstrong, 1970). Uranium deposits are hosted by the Puddle Spring Arkose Member of the Wind River Formation. Folded and faulted Mesozoic and Paleozoic rocks are visible within the northwest-southeast trending Dutton Basin anticline north of the Gas Hills Uranium District. The Oligocene White River Formation (300-650 ft. thick) unconformably overlies the Wagon Bed Formation, but in a few localities the White River Formation overlies the Wind River Formation where the Wagon Bed Formation was removed by pre-White River Formation erosion. Figure 11 shows the stratigraphy of the Gas Hills Uranium District.

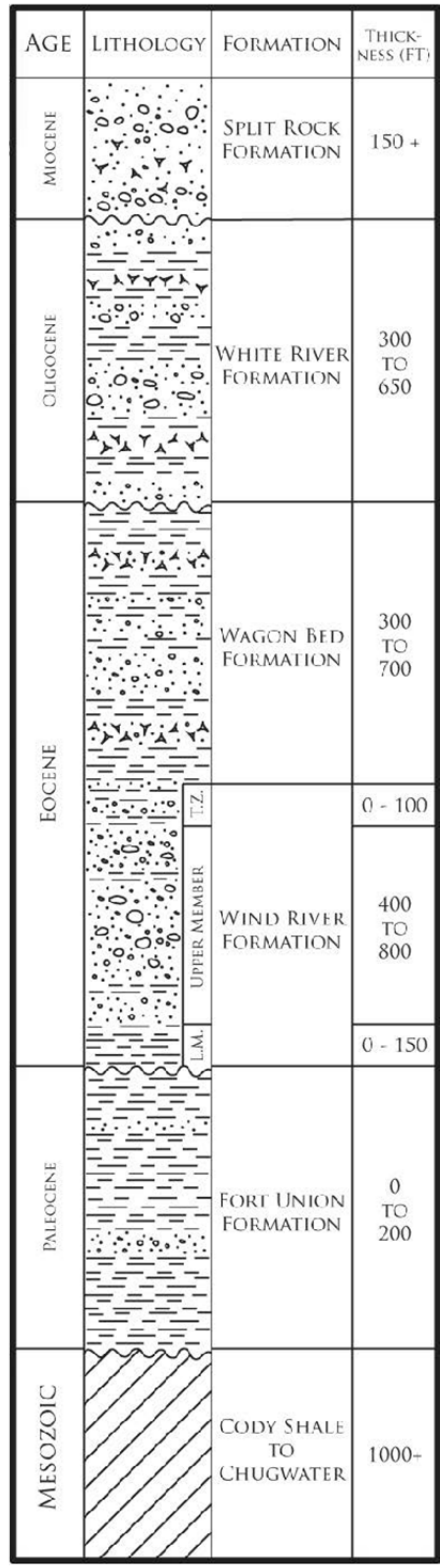


Figure 11 - Stratigraphy of the Gas Hills Uranium District (Snow, 2011)

Beaver Divide is a significant physiographic and geologic feature of the Gas Hills District. This feature exerts a strong control on the mining method practical for uranium recovery. Near Beaver Divide uranium-bearing strata are too deep for open pit mining and require ISR or underground mining methods for recovery. Moving north of Beaver Divide, uranium hosting strata are shallow enough for more cost-effective open pit mining methods (Figure 12).

A summary of the geologic history of the Granite Mountains is necessary to understand the significance of Beaver Divide to uranium mining in the Gas Hills. The Granite Mountains were first uplifted and thrust to the south in Paleocene time to form a large range similar in size and structure to the Wind River Mountains. Sediments eroded from these mountains and surrounding Laramide mountain ranges eventually filled the intervening basins and partially covered the Granite Mountains. These deposits now constitute the Eocene Wind River and Wagon Bed Formations, the Oligocene White River Formation, and the Miocene Split Rock Formation. In Late Miocene time, the central portion of the Granite Mountains was down-dropped to form a large east-west trending trough, or graben, roughly 25 miles by 60 miles in extent. The northern and southern boundaries of this graben are marked by large east-west trending normal faults. Beaver Divide roughly coincides with the north bounding, south dipping normal fault. South of this fault, rocks have been down-dropped placing the uranium-hosting Wind River Formation at greater depths below the surface (500-900 ft depth) as opposed to north Beaver Divide where uranium-bearing strata are encountered at depths of 0 to 600 ft. deep (Figure 12).

Geology of Gas Hills Uranium Deposits

Uranium deposits in the Gas Hills are confined to permeable sandstone units of the Puddle Spring Arkose Member of the Wind River Formation and occur as roll-front deposits. Sandstone roll-front deposits are crescent shaped in cross-section (Figures 13 & 14), extremely sinuous in plain view, and extending for several miles (Figure 9).

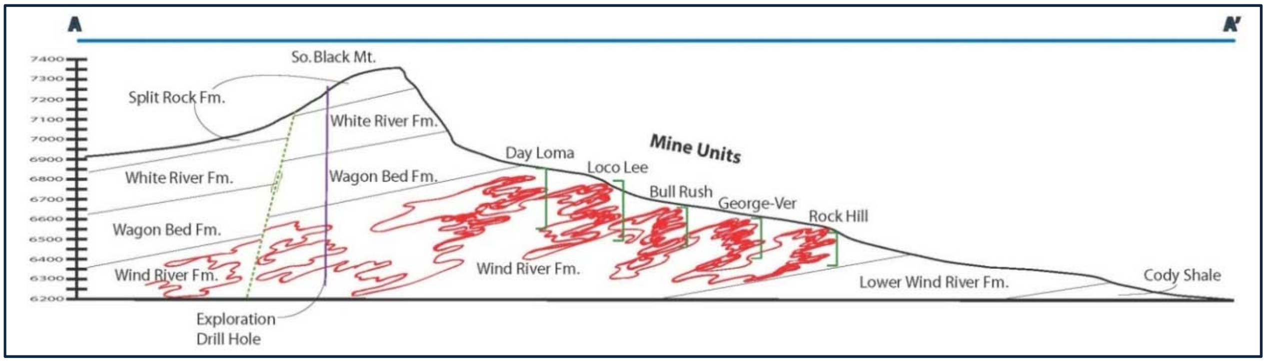


Figure 12: North-south structural cross section of the Gas Hills Uranium District, Wyoming (Strathmore Minerals Corp., 2010)

Figure 13: Photo of uranium roll-front exposed during reclamation of the George-Ver open pit. Compare with figure 14. (Snow, 2011)

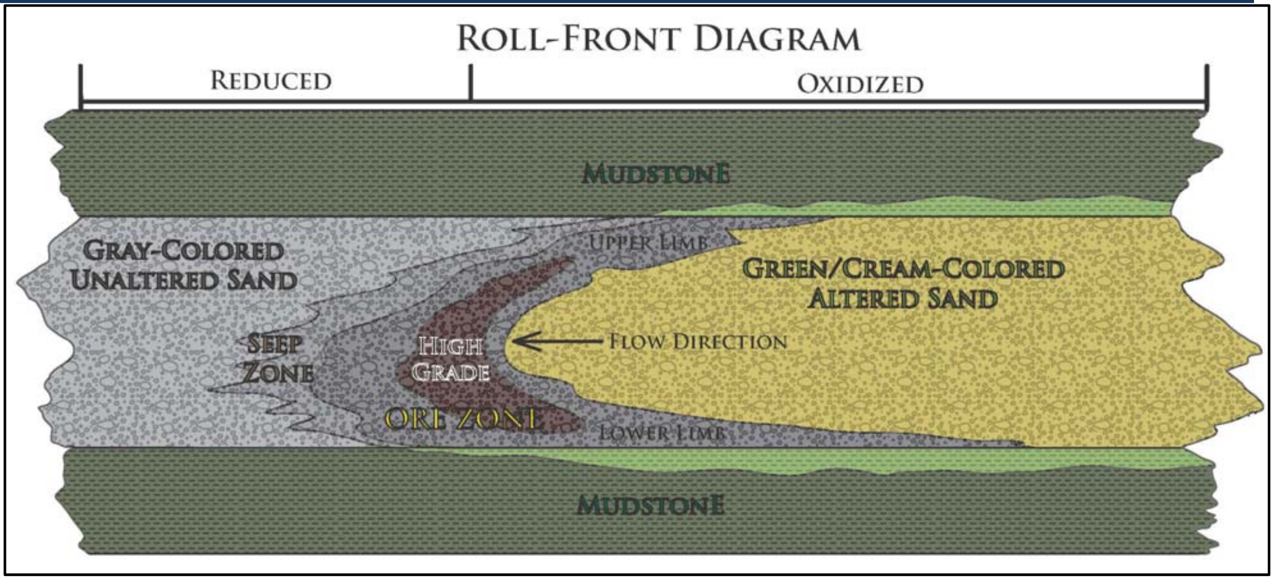


Figure 14: Idealized Gas Hills District uranium roll-front (Snow, 2011)

Sandstone roll-front uranium deposits form as uranium-rich groundwater flows through a sandstone aquifer. Uranium and other metals, such as molybdenum, vanadium, selenium, and arsenic, precipitate from the groundwater as it encounters an oxidation/reduction interface in the sandstone. Figure 14 illustrates an idealized Gas Hills uranium roll-front ore body. Individual rolls vary in vertical extent from a few inches to up 20 feet thick. The upper limb ore generally pinches out abruptly, while the lower limb ore is greatly extended horizontally and gradually pinches out. Roll fronts may also be vertically staked *en echelon* where impermeable beds occur between stacked sandstone bodies. The roll front marks the boundary between unaltered sandstone where the uranium rich fluids did not pass and altered sandstone that the uranium bearing solutions have passed through. The altered sandstone through which the mineralizing fluids have passed is characterized by altered feldspar and an absence of limonite specks. Unaltered sandstone located down gradient from the roll-front, is typically greenish-gray with sparse limonite specks. Difference is pyrite morphology also enables distinction between unaltered and altered sandstone. Pyrite in the altered sandstones occurs as discrete, euhedral (well-formed) crystals while smaller, less well-formed pyrite is characteristic of unaltered sandstone (King and Austin, 1966).

Unoxidized uranium ore in a roll-front is typically dark colored with the darkest ore correlating to higher grades. Ore minerals consist of extremely fine grained uraninite (UO_2) and lesser coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$). Within the 'high grade' portion of the deposit ore grade can be up to several percent, by weight, U_3O_8. Toward the altered sandstone there is a sharp decrease in grade and a well-defined contact between ore and waste. Moving towards the unaltered sandstone, the ore grade gradually decreases. Ore grades as low as 0.05% U_3O_8 are considered economic as open pit mining projects.

Day 2:

- Oil Shale – Green River Formation
- South Pass City/Atlantic City Mining District

Lander to South Pass Roadside Geology

Southeast of Lander, Wyoming Highway 28 climbs the eastern flank of the Wind River Mountains towards South Pass encountering progressively older northeast dipping strata. A general cross section of the Wind River Mountains is located on the Wyoming state geologic map in the map pocket of the field trip guidebook.

Initially, the highway traverses over Cretaceous shale. South of the junction of U.S. Highway 287 and WY highways 28 about 10 miles southeast of Lander, exposures of the Cretaceous Mowry Formation appear to the northeast (left). The silvery colors of the Mowry Formation are distinctive, and due to the presence of silica cement which causes it to be more resistant to weathering and erosion than most shale. Fish scales are also abundant in the Mowry Formation. To the southwest, is a dip-slope underlain by sandstone and mudstone of the Cretaceous Cloverly and Jurassic Morrison formations.

The highway then turns southwest and begins to climb the southern end of the Wind River Mountains. From this point, progressively older formations are encountered. The Jurassic Sundance Formation is poorly to moderately well exposed on the hillsides to the west. Cliffs of orange-colored, cross-bedded sandstone of the Lower Jurassic Nugget Formation are the exposed to the southeast (left) of the highway. The Nugget Formation, restricted to southwestern Wyoming, correlates with the Navajo Sandstone of Utah (Nielsen, 2010).

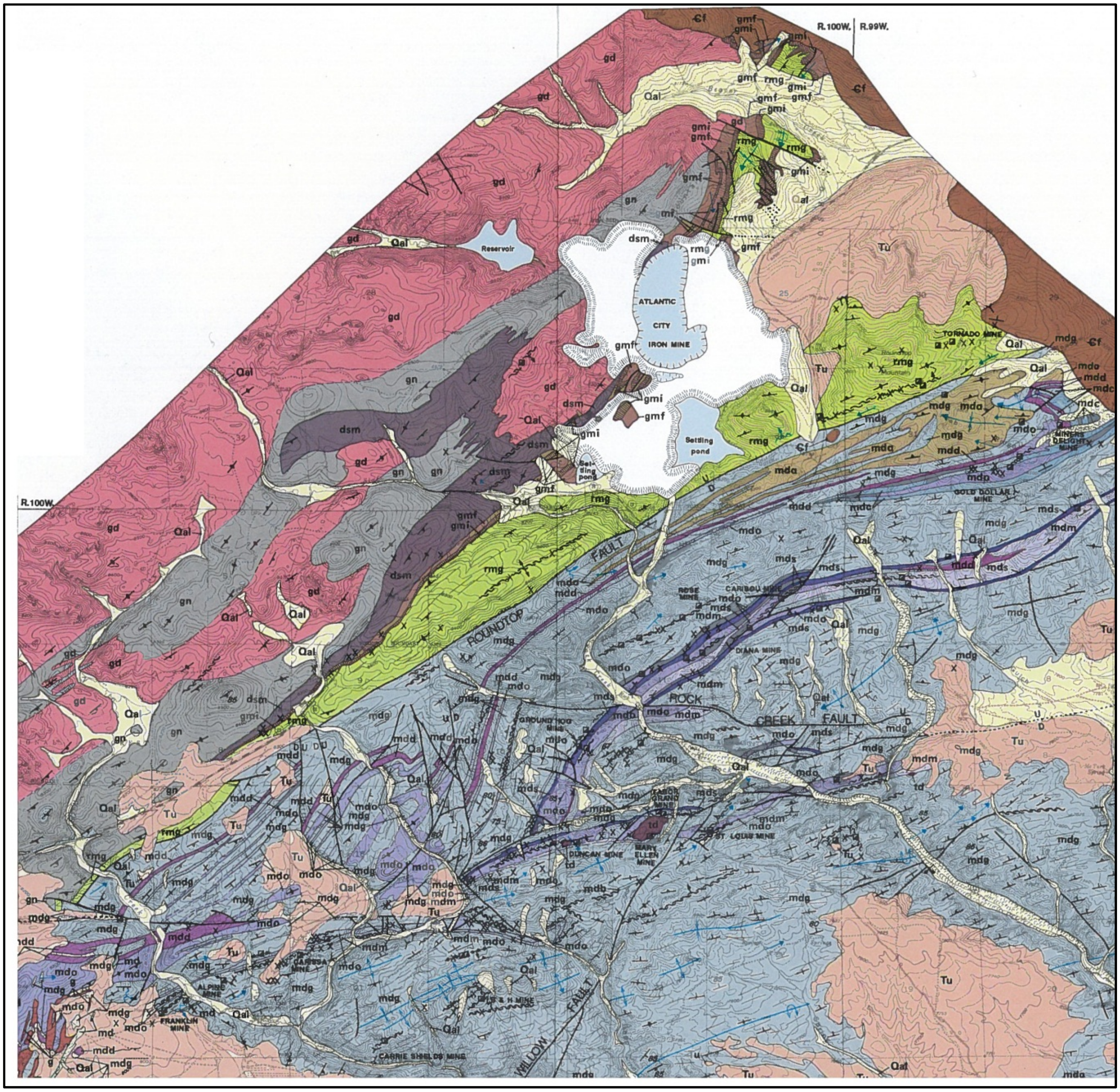
Continuing on the highway, the next formation to outcrop is the Triassic Chugwater Group composed of red-orange sandstone and siltstone, with an occasional limestone bed. The Red Canyon Overlook, just beyond the first highway exposures is a spectacular place to view this formation. The dip slope to the west of Red Canyon is underlain by limestone of the Permian Phosphoria Formation.

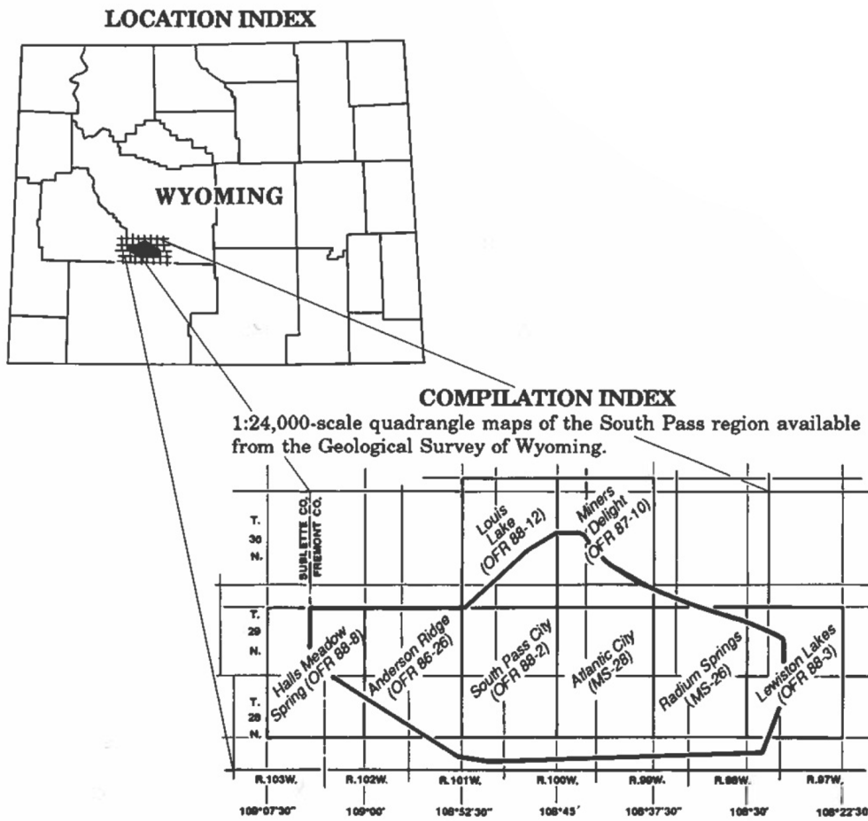
As the highway continues to climb exposures of the Tensleep, Madison, Bighorn, and Flathead Formations are encountered, but the outcrop quality pales in comparison to those observed in Tensleep and Wind River Canyons.

Archean Rocks of the South Pass Granite-Greenstone Belt

After passing the Flathead Formation outcrops, the bedrock consists of metamorphic and igneous rocks of the South Pass Archean Granite-Greenstone Belt which represent the structural core and oldest rock unit of the Wind River Mountains. Figure 15 shows a portion of the Geologic Map of the South Pass Granite-Greenstone belt.

Figure 15: Geologic Map, Location Index, and Legend of the South Pass Granite-Greenstone Belt (Hausel, 1990)





* This work was partially funded with support from the Geological Survey of Wyoming administrative budget; by U.S. Geological Survey COGEOMAP GRANTS 14-08-0001-A0226, 14-08-0001-A0396, and 14-08-0001-A0454; and by a U.S. Geological Survey Sweetwater Rocks wilderness study grant.

PHANEROZOIC SEDIMENTARY ROCKS AND SURFICIAL DEPOSITS

PHANEROZOIC

Qal — **QUATERNARY ALLUVIUM** –Unconsolidated stream gravel, sand, silt, and clay. Locally includes placer gold deposits and other heavy minerals such as scheelite and rare cassiterite.

unconformity

Tu — **TERTIARY UNDIVIDED**[1]– Tuffaceous, arkosic sandstone, claystone, siltstone, and conglomerate. Locally includes unconsolidated Quaternary stream gravels. Conglomerates contain paleoplacer gold in some areas. (See text for more detailed description of Tertiary strata.)

unconformity

Ꞓf — **FLATHEAD SANDSTONE (CAMBRIAN)** – Crossbedded arkosic sandstone, quartzite, and conglomerate.

INTRUSIVE IGNEOUS ROCKS

PROTEROZOIC

unconformity

md — **MAFIC DIKES (PROTEROZOIC)** – Fine- to medium-grained basaltic and diabasic dikes (1.27 to 2.0 Ga[2]).

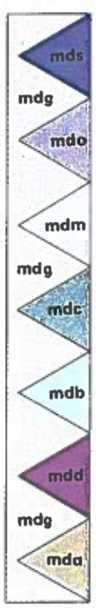
g — **GRANITE (ARCHEAN)** – Granite and granite pegmatite.

gd — **GRANODIORITE (ARCHEAN)** – Biotite-hornblende quartz diorite and granodiorite. Includes 2.6 Ga[3] granodiorite of the Louis Lake batholith in the northwest and the Lewiston Lakes pluton in the southeast.

td — **TONALITE (ARCHEAN)** – Medium- grained leucodacite porphyry and quartz diorite dikes and tonalite plugs.

SOUTH PASS GREENSTONE BELT META-SEDIMENTARY AND METAIGNEOUS ROCKS

ARCHEAN



MINERS DELIGHT FORMATION[1] (ARCHEAN)

mdg, metagreywacke – feldspathic and biotitic metagreywacke, and mica schist. Hosts several epigenetic shear zone and vein gold deposits. Rb-Sr whole-rock isochron about 2.8 Ga.[3]

mds, graphitic schist – black, iron-stained schist; commonly sheared. Locally contains quartz stringers, veins, and gold mineralization.

mdo, mafic amphibolite – black hornblendic amphibolite with fine- and medium-grained texture. Includes metamorphosed gabbro dikes and sills and basalt flows. Locally, hosts auriferous shear zones.

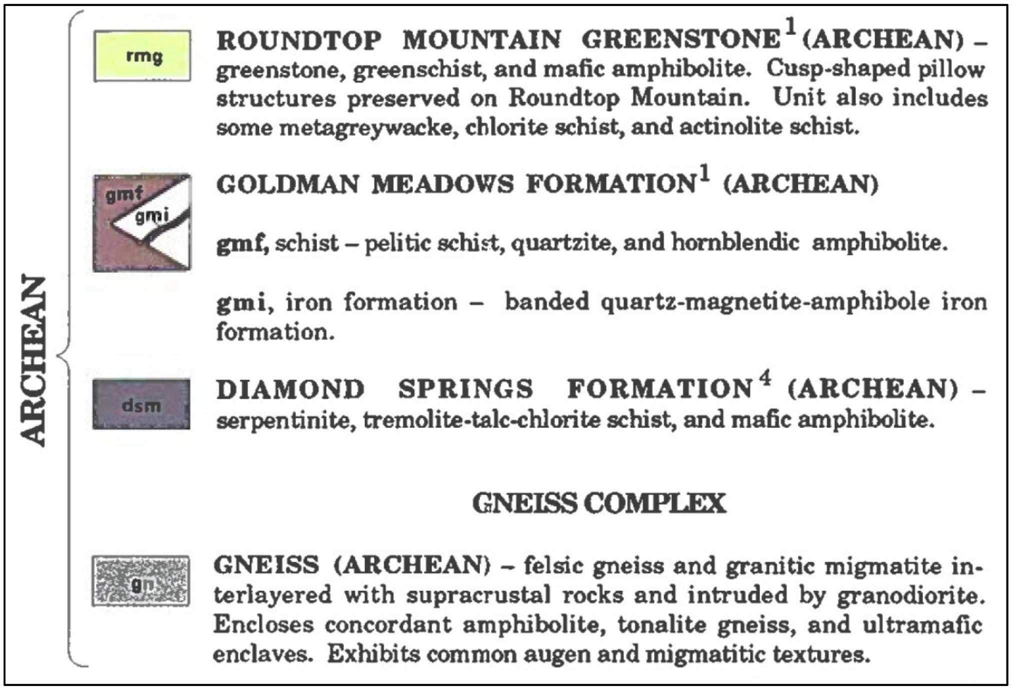
mdm, mixed member – mixed unit of fine-grained mafic metavolcanics, metagreywacke, tremolite-actinolite schist, and chlorite schist, with local interbeds of metaconglomerate.

mdc, metachert – interlayered cherty metagreywacke, ultramylonite, and metagreywacke.

mdb, marble – fine- to medium-grained metacarbonate, locally sulfide-bearing.

mdd, metadacite – black metadacite porphyry flows and sills (?) with plagioclase phenocrysts (porphyroblasts) aligned in trachytic texture.

mda, meta-andesite–ellipsoidal and nonellipsoidal meta-andesite flows.



With the presence of 'stratigraphic top' indicators such as graded beds and lava pillows, the stratigraphic sequence here is well established. The supracrustal sequence begins with the Goldman Meadows Formation composed of quartzite, iron formation and pelitic schist. The Atlantic City Iron Mine, operated by U.S. Steel from 1960 to 1982, exploited quartz-magnetite-amphibole banded iron formation from this formation. Banded iron formation is commonly interpreted as marine chemical sediments.

The Goldman Meadows Formation is overlain the by Round Mountain Greenstone which is a metavolcanic unit that consists of greenstone, greenschist, and vesicular and pillowed metabasalt (Hausel, 1990). Excellent exposures outcrop south of the highway in an old railroad cut to the southeast of the iron mine.

The Miner's Delight Formation is likely the youngest unit in the sequence although it is in fault contact with the Round Mountain Greenstone. The Miner's Delight Formation, which hosts gold mineralization, is dominantly metagraywacke, metatuff, metaconglomerate, and meta-andesite (Hausel, 1990). This sequence is then intruded by a diverse array of igneous rocks such as peridotite, diabase dikes and sills, diorite dikes and sills, and granodiorite of the Louis Lake Batholith. Miner's Delight Formation hosts gold mineralization and will be examined at the Carissa Mine and South Pass City stops later in the day.

The supracrustal sequence consisting of the three aforementioned formations, was then subjected to two at least two episodes of folding, faulting, and development of foliation (Worl and Houston, 1993). The age of this sequence is not precisely known, but rubidium-strontium whole rock isochron dating suggests an age of about 2,800 Ma (Peterman, 1982). Certainly these rocks are older than the granodiorite, quartz diorite, and quartz monzonite of the Louis Lake Batholith which intrudes this sequence. Uranium-lead zircon and rubidium-strontium whole rock dating techniques establish a 2,630 +/- 20 Ma age for the Louis Lake Batholith (Stuckless et. al., 1985). West of the Atlantic City Iron Mine, outcrops of the Louis Lake Batholith and associated gneisses appear to the north.

Look for occasional remnants of the Miocene sediments that rest unconformably upon the Archean rocks. These sediments were deposited after the Laramide orogeny and nearly buried the Laramide uplifts. Erosion since the Miocene has exhumed the Laramide uplifts leaving remnants of these deposits perched in the mountains.

The Green River Basin Roadside Geology

Wyoming Highway 28 descends from South Pass over the continental divide to the southwest into the broad, flat, sagebrush-covered Green River Basin (also known as the Bridger Basin). This low spot in the continental divide was discovered in 1824 by famed mountain man Jedediah Smith. This became the favored route for westward immigration – the Oregon Trail.

Continuing along Highway 28 to the southwest, Miocene sandstone and claystone cover the Archean igneous and metamorphic rocks for the next four miles past the Continental Divide area. The Eocene Wasatch Formation is the next formation to be encountered. Look for sandstones and varied-colored claystone and siltstone in occasional bad land outcrops.

The Wind River thrust fault is crossed about five miles past the Continental Divide but is buried beneath the Wasatch Formation. Seismic reflection profiling constrains the location and dip of this fault and confirms that a large wedge of Archean rock was thrust to the southwest over Eocene and older sedimentary rocks (see cross-section on the Wyoming state geologic map).

After about thirteen miles of Wasatch Formation, the road passes over the Laney Member of the Eocene Green River Formation to Farson and Eden, Wyoming. The brown to tan oil shale and limestone of the Laney Member contains fish fossils, but is generally not well exposed. Collecting vertebrate fossils on this federal land, managed by the Bureau of Land Management, is illegal without a research permit.

Stratigraphy and Geologic Setting of the Green River Formation

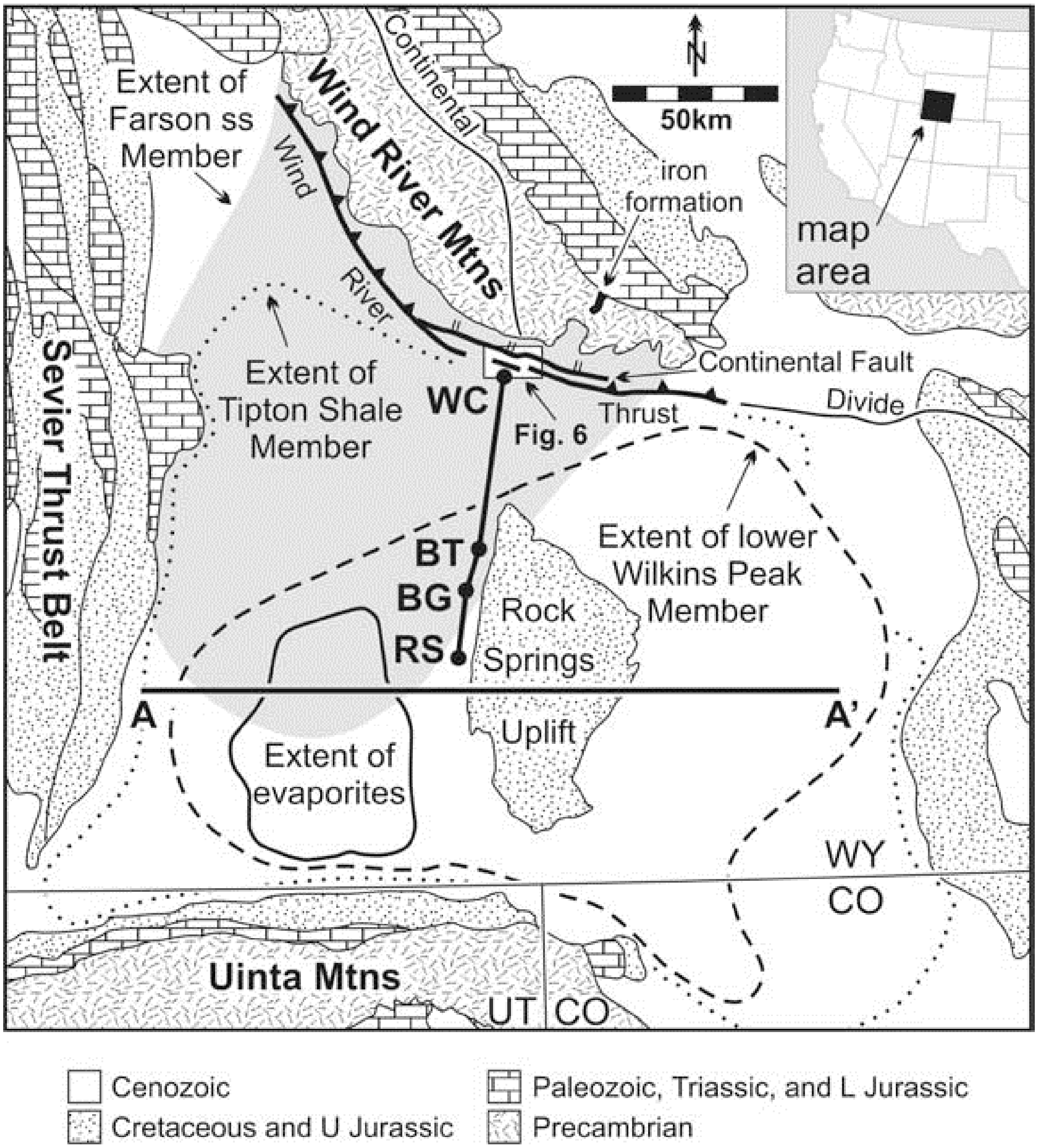


Figure 16: Simplified geologic map of the Greater Green River Basin. Day 2 Green River Formation field stop is labeled BT – Boar's Tusk (Pietras *et. al.*, 2003)

The Lower to Middle Eocene Green River Formation records deposition in a series of intermountain lakes generally bounded by Laramide uplifts. Three major basins contain these deposits: the Green River Basin of Wyoming, the Piceance Basin of Colorado, and the Uinta Basin of Utah. The Greater Green River Basin is bounded on the west by the Wyoming Fold and Thrust Belt, on the east by the Rawlins Uplift and Sierra Madre Mountains, to the north by the Wind River Range, and to the south by the Uinta Mountains. Lake Gosiute occupied the Green River Basin during the much of the Eocene Epoch.

Four phases of Eocene Lake Gosiute are recorded by the Green River Formation in Wyoming. These include from oldest to youngest: the Luman Tongue, Tipton Shale Member, Wilkins Peak Member, and Laney Member. The lacustrine deposits of the Green River Formation grade laterally into the alluvial deposits of the Eocene Wasatch Formation which also underlies the Green River Formation.

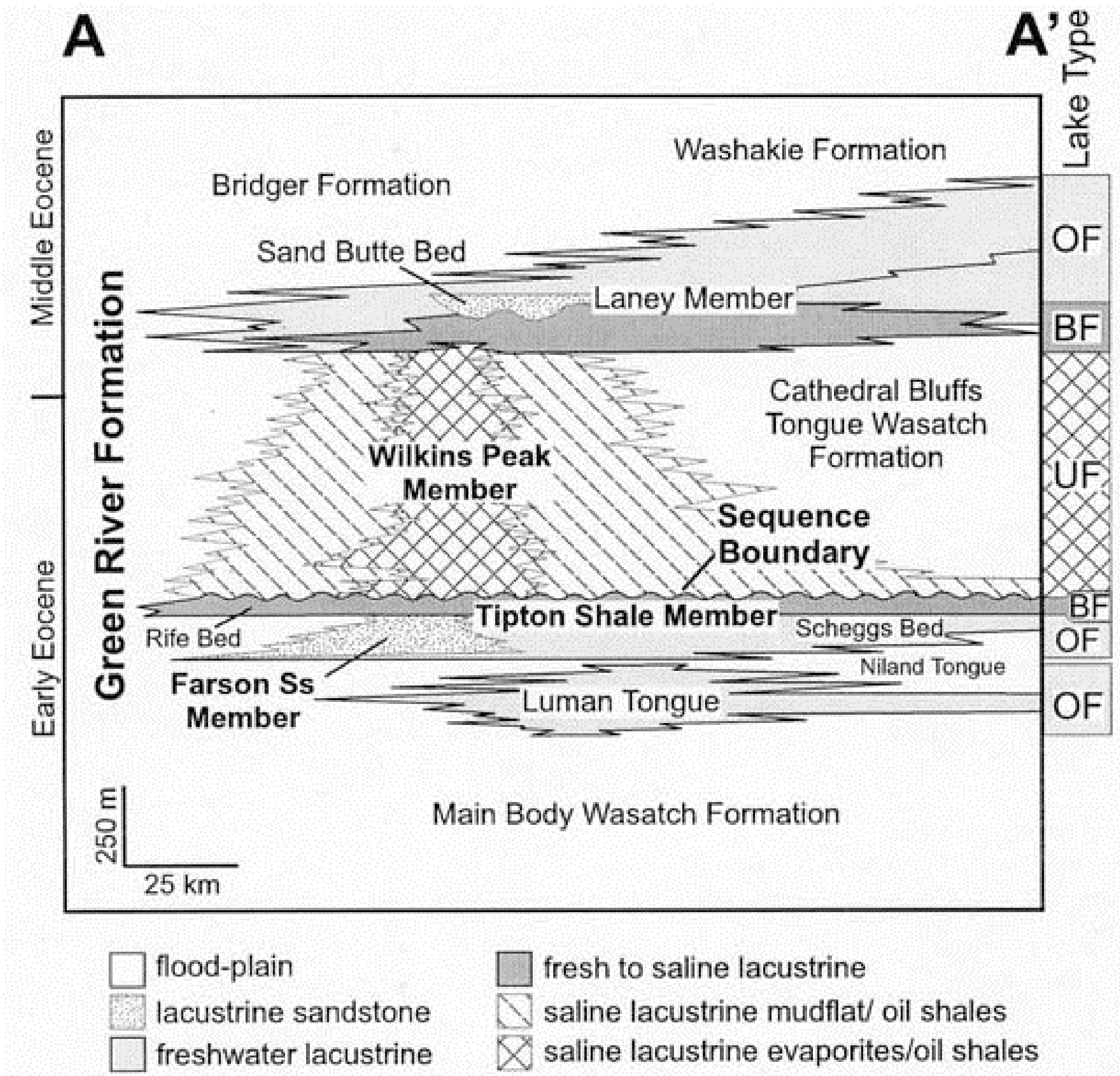


Figure 17: Cross section illustrating the regional Eocene stratigraphy of the greater Green River Basin. See Figure 16 for location of cross section. Lake-basin types from Carroll and Bohacs (1999) OF – overfilled, BF – balanced fill, UF – underfilled (Pietras *et. al.*, 2003)

Changes in the lake levels and tectonic pulses resulted in complex interfingering relationship between these two formations as tongues of alluvial sands periodically prograded into the lake basin.

Oil shale, carbonaceous shale, and sandstone of the Luman Tongue are interpreted as freshwater lacustrine deposits and are separated from the main body of the Green River

Formation by the Niland Tongue of the Wasatch Formation. The Tipton Shale Member also records freshwater lake conditions, the Wilkins Peak Member records hypersaline evaporative lake conditions, and freshwater lake condition returned again as recorded by the Laney Member (Hanley, 1976; Roehler, 1992a; Roehler, 1993). Lake Gosiute disappeared in the Middle Eocene as fluvial deposits of the Bridger Formation filled the lake basin (Pietras et. al., 2003).

Oil Shale Resources in the Green River Formation

The term 'oil shale' is a misnomer. It is neither true shale, nor does it contain true petroleum. Marlstone, consisting of about half clay and half lime mud sediments, is the dominant rock type of oil shale deposits in the Green River Formation. True shale is dominated by silicate clay minerals.

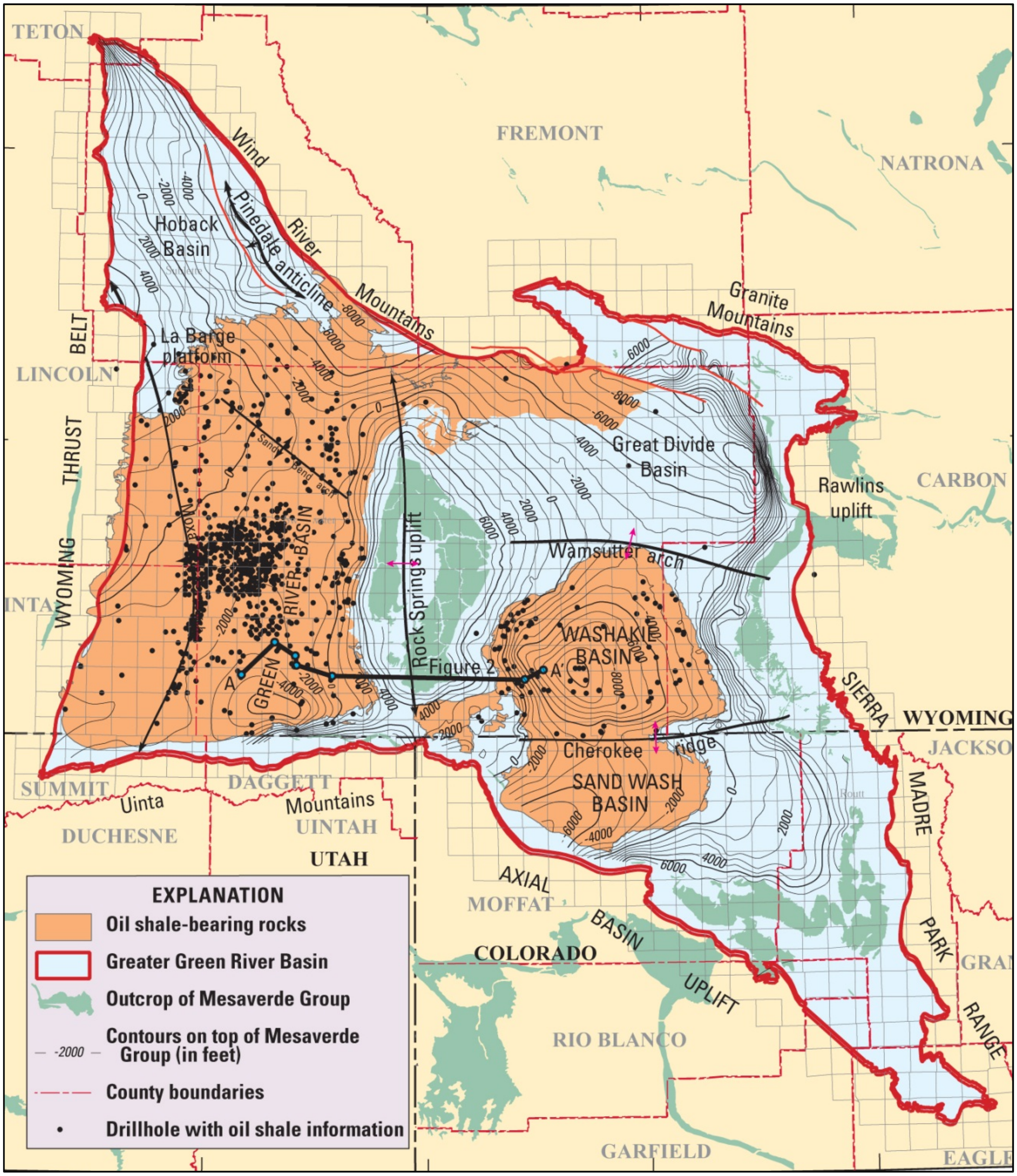


Figure 18: Map showing boundary (in red) of the Greater Green River Basin of Wyoming, Colorado, and Utah. Areas underlain by oil shale-bearing rocks and the location of drill holes with oil shale information are also shown (Johnson *et. al.,* 2011).

The 'oil' in these rocks is kerogen. Kerogen is a solid hydrocarbon, in this case derived from algal remains, that has not reached thermal maturity required to produce petroleum. However, the kerogen in these rocks can be converted to petroleum by either *in-situ* or *ex-situ* thermal processing. Figure 18 shows the distribution of oil shale-bearing rocks within the Green River Basin. A summary of past and present oil shale processing technology is included below.

The United States Geological Survey (Johnson *et. al.,* 2011) has recently published estimates of the total in-place oil shale resources for the Green River Formation within the Greater Green River Basin of Wyoming and adjoining areas of Colorado and Utah. Total in-place resources are estimated at 1.44 trillion barrels of oil. This total is divided among three assessed units: Tipton Shale Member at 362,816 million barrels of oil (MMBO); Wilkins Peak Member at 704,991 MMBO; and the LaClede Bed of the Laney Member at 377,184 MMBO. Total in-place oil shale resources for the Green River Formation in the Piceance Basin of Colorado are estimated at 1.53 trillion barrels of oil, while those of the Uinta Basin of Utah are estimated at 1.32 trillion barrels of oil (Johnson et. al., 2010a and 2010b). While the total resources are comparable among the these three basins, the area of the Green River Formation is much larger than the Piceance and Uinta Basins, making these deposits the lowest grade of the three basins. As such past and current research, development, and demonstration of oil shale extraction technology has been centered on the Piceance and Uinta Basins. It should also be emphasized that this total of 4.29 trillion barrels of oil is not all recoverable given current technology and market conditions. However, compared to proven global oil reserves (defined as quantities of oil that are reasonably certain to be recoverable using existing technology and under existing economic conditions) of about one trillion barrels of oil Green River oil shale presents an enticing opportunity for the next generation of engineers and geologists.

Ex-situ **Commercial Oil Shale Production**

Enefit American Oil (formerly known as Oil Shale Exploration Company – OSEC) holds approximately 30,000 acres of oil shale leases in the Uintah Basin of Utah. Enefit American Oil (EAO) is a subsidiary of Eesti Energia, an Estonian energy company with nearly a century of experience mining and retorting oil shale. EAO is currently conducting baseline environmental monitoring, mine planning, reserve reporting, and mineral properties testing in preparation to re-open the abandoned White River Oil Shale Mine, south of Vernal, Utah, and to construct a new oil shale mine on nearby private land. These two mines will be connected by a seven mile tunnel. An onsite Galoter retort, a horizontal retort that utilizes a circulating fluidized bed combustion processes, will process the oil shale to produce an 20-25 API gravity oil which will then be hydrotreated to remove nitrogen and sulfur producing a final API 35 gravity oil. Gary Aho of Enefit American Oil estimates that permitting will be complete by 2016 and mine construction will begin in 2017. By 2020, the project will produce 25,000 barrels of oil per day (bopd) ramping to 50,000 bopd by 2024. EAO estimates the total cost per barrel of oil, which includes capital and operating costs, is $45-50.

Summary of New R&D *In-situ* Oil Shale Extraction Technologies

Commercially viable *ex-situ* processing of oil shale has been operating for decades in China, Estonia, and Brazil. Oil shale is mined underground or at the surface, crushed, then conveyed to a retorting plant where it is heated and converted to crude oil, water, and gas. While no ex-situ retorting technologies have been demonstrated commercially in the United States numerous experimental *ex-situ* technologies have shown promise such as the Paraho process surface retort near Rifle, Colorado (Wasilk and Robinson, 1980).

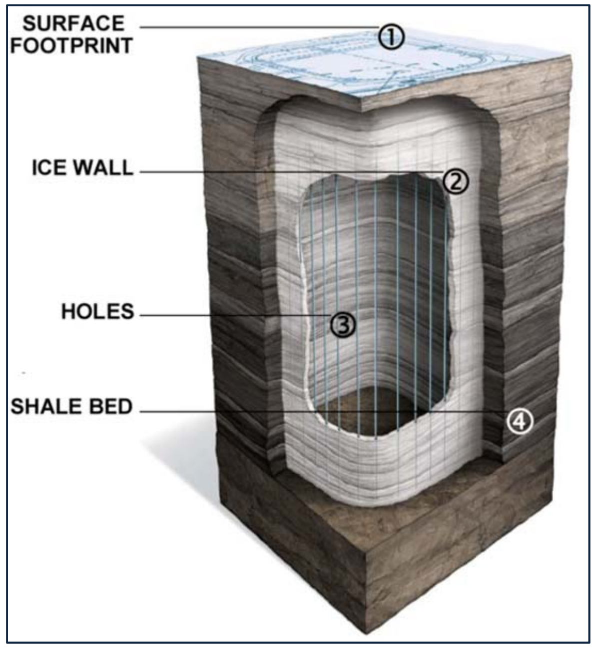


Figure 19 : Shell Oil's ICP freeze wall (Shell Frontier Oil and Gas, 2006)

Shell Oil's *In-situ* Conversion Process (ICP)

Shell's ICP process seeks to isolate the production zone by producing a 'fence' consisting of numerous 2000 foot-deep wells on eight foot spacing (Figure 19). A super-chilled fluid is circulated through these wells to cool the ground to -60^{o} F and produce a freeze wall that isolates the production zone from groundwater. A freeze wall is produced in six to twelve months of cooling.

Next, a series of heating and production wells are then drilling into the central working zone at forty foot spacing. Electric heating elements are lowered into the heating wells to bring the temperatures of the production zone to 650^{o} to 700^{o} F for a period of about four years. Kerogen is then converted to petroleum and natural gas and recovered via the production wells (Shell Frontier Oil and Gas Inc., 2006). Figure 20 illustrates the geometry of the heating and production wells.

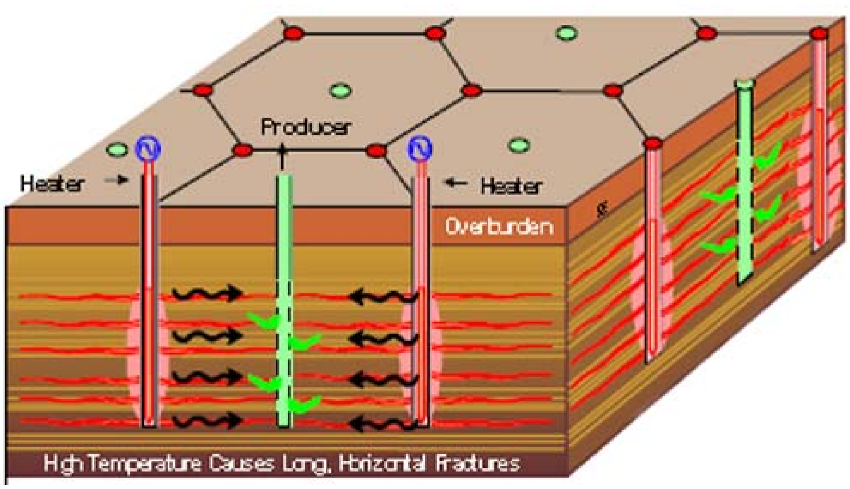


Figure 20 : Schematic of Shell Oil's ICP (Shell Frontier Oil and Gas, 2006)

While the energy return compared to the energy invested is low compared to conventional crude oil production, Shell estimates a return of three to four energy units for each energy unit invested. This compares to existing nonconventional petroleum extraction processes such as the heavy oil sands projects of Alberta, Canada.

Exxon-Mobil's Electrofrac Process

In this process, a series of vertically-oriented hydraulic fractures are first created from horizontal wells. Calcined coke is then injected into the fractures to produce an electrically conductive material which acts as a heating element. A second horizontal well is then drilled to intersect the toe of the horizontal well that is parallel to the fracture (Figure 21). Electric current is then passed through the coke-lined fracture heating the kerogen to produce petroleum and natural gas which is recovered from a series of separate vertical production wells. The large surface area of these planar heaters is an advantage over well bore heaters in that fewer are required to mature a similar volume of oil shale reducing surface impacts (Symington et. al, 2008)

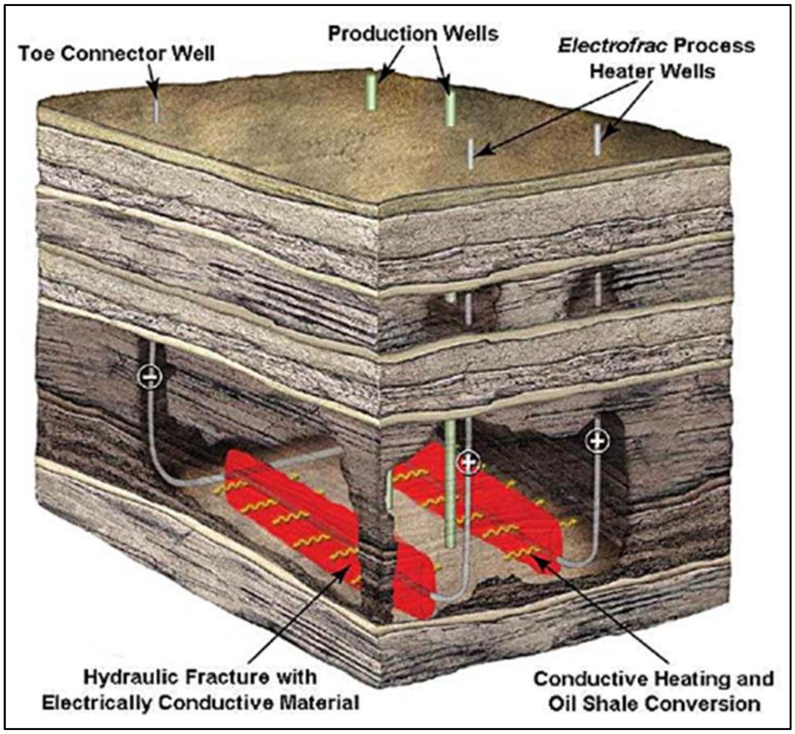


Figure 21: Exxon-Mobile's Electrofrac Process (Symington et. al, 2008)

Successful laboratory experiments have led to current field testing of this technology at the Colony Mine located in Parachute Creek south of Rifle, Colorado.

Chevron's CRUSH Process

Developed jointed with Los Alamos National Laboratory, **C**hevron's Technology for the **R**ecovery and **U**pgrading of Oil from **Sh**ale, or CRUSH process, uses heated carbon dioxide to convert kerogen into petroleum and natural gas. First, a series of vertical wells are drilled into the oil shale zone. Horizontal fractures are then produced by carbon dioxide injection. Pressurization of the heated carbon dioxide and the use of propellants and explosives rubblize the production zone and mature the kerogen. Separate production wells extract the petroleum and natural gas (Figure 22). Used carbon dioxide is recycled and reheated and residual kerogen in formerly heated and depleted zones is combusted in-situ to generate heated gases to created new rubblized production intervals.

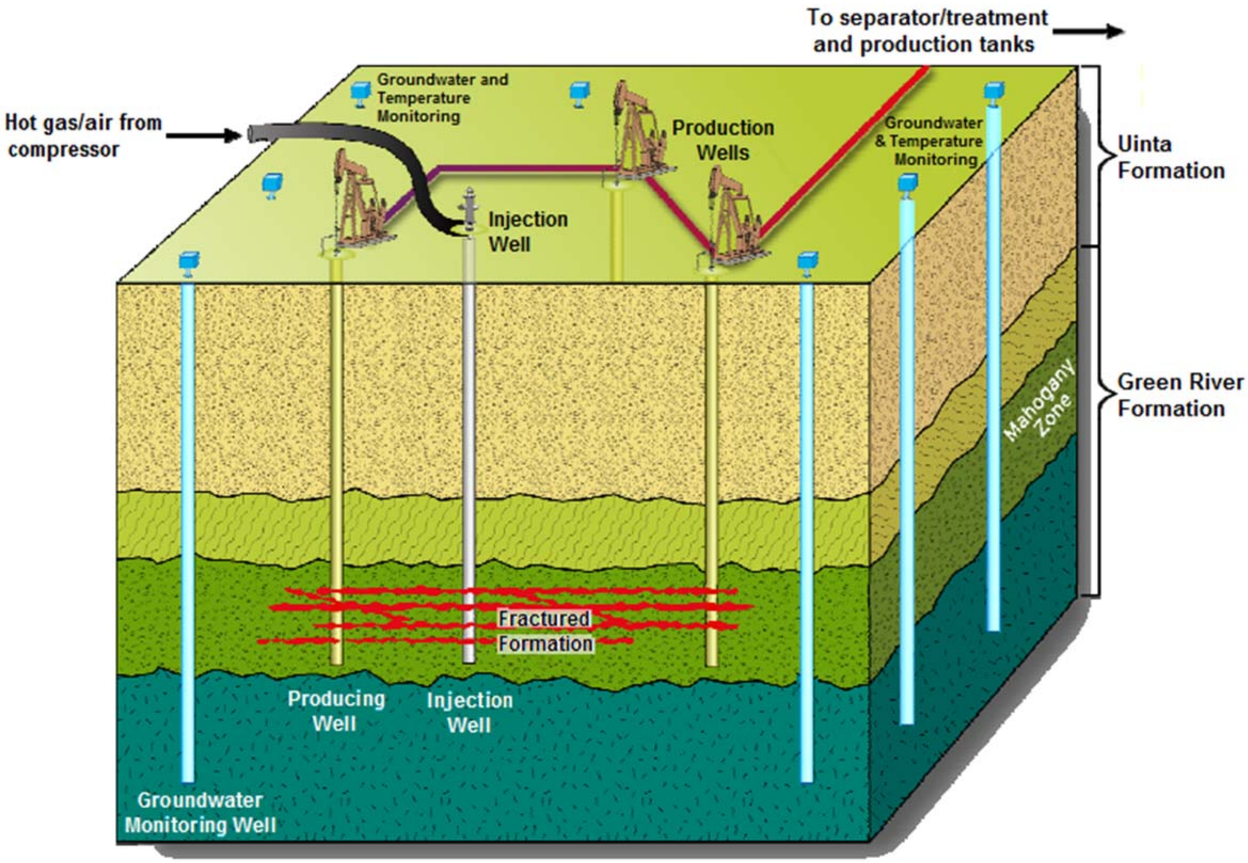


Figure 22: Chevron's CRUSH process

Hybrid *In-situ/Ex-situ* Oil Shale Extraction Technology

Red Leaf Resources EcoShale In-Capsule Process

Red Leaf Resources' EcoShale™ In-Capsule Technology was developed to produce petroleum from oil shale. This process may also be used for oil sands, coal, lignite, and bio-mass. In this process, an encapsulated surface impoundment is constructed around a body of mined oil shale. Hot gases are circulated through pipes that penetrate the capsule and mature the kerogen to petroleum (Figure 23).

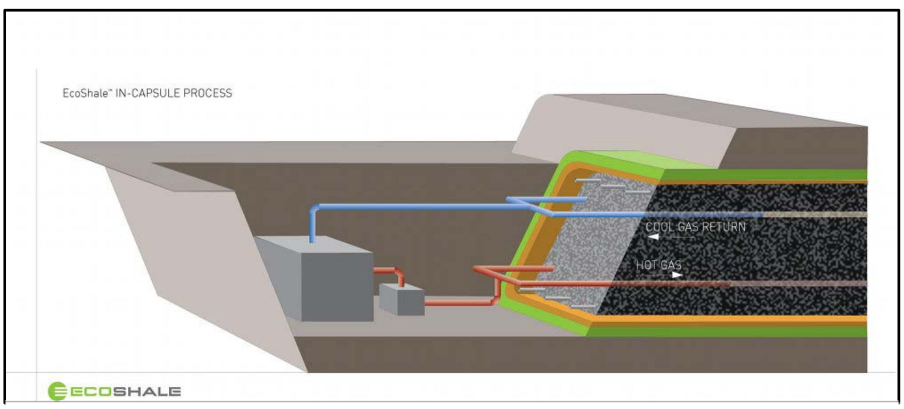


Figure 23: Red Leaf Resources EcoShale In-Capsule Process

Environmental benefits of this process include no process water requirements and ex-situ maturation which protects against groundwater contamination which is an issue with all in-situ processes.

A successful pilot test of the EcoShale In-Capsule technology was completed at Seep Ridge in the Uintah Basin of Utah in 2009. Red Leaf Resources believes that this technology may be applied at various scales and is planning a 9,500 barrel of oil per day commercial project at Seep Ridge with first oil production projected for 2012 (Red Leaf Resources, 2011).

Day 2 Energy Site Visit – Oil Shale

White Mountain and Boar's Tusk Field Site

A few miles south of Eden, the field trip route follows a Bureau of Land Management road to White Mountain and the Boar's Tusk. After about four miles, a decent exposure of Laney Member of the Green River Formation appears to the north.

After about nine miles, the Killpecker Dune Field is visible to the east. These dunes are part of a fifty mile long, east-west trending dune field produced as the prevailing westerly winds are funneled through South Table Mountain and Steamboat Mountain, also visible on the eastern horizon. These mountains are part of the Leucite Hills, a Pleistocene volcanic field named for the mineral leucite which occurs in rare, potassium-rich volcanic rocks. In the 1860s, soldiers of the U.S. Calvary named Killpecker Creek, which flows through the valley below, for the effect that its alkaline waters apparently had upon their bodily functions!

The Boar's Tusk is a volcanic neck that rises about three hundred feet above the Killpecker Creek valley floor. It is composed of a very rare, ultrapotassic volcanic rock called Wyomingite.

Wyomingite is a phlogopite leucite lamproite. The neck is composed of agglomerate that contains xenoliths of Green River and Wasatch Formation, Wyomingite autobreccia, and some granitic xenoliths.

White Mountain is the erosional escarpment visible to the west after the road turns to the south beyond the turnout to Chicken Springs. White Mountain exposes the Tipton Shale and Wilkins Peak Members of the Green River Formation and is the focus of this leg of the field trip.

Figure 24 shows a measured section across the Tipton Shale/Wilkins Peak contact from the Boar's Tusk area and correlations with other measured sections of the Green River Formation along the White Mountain escarpment.

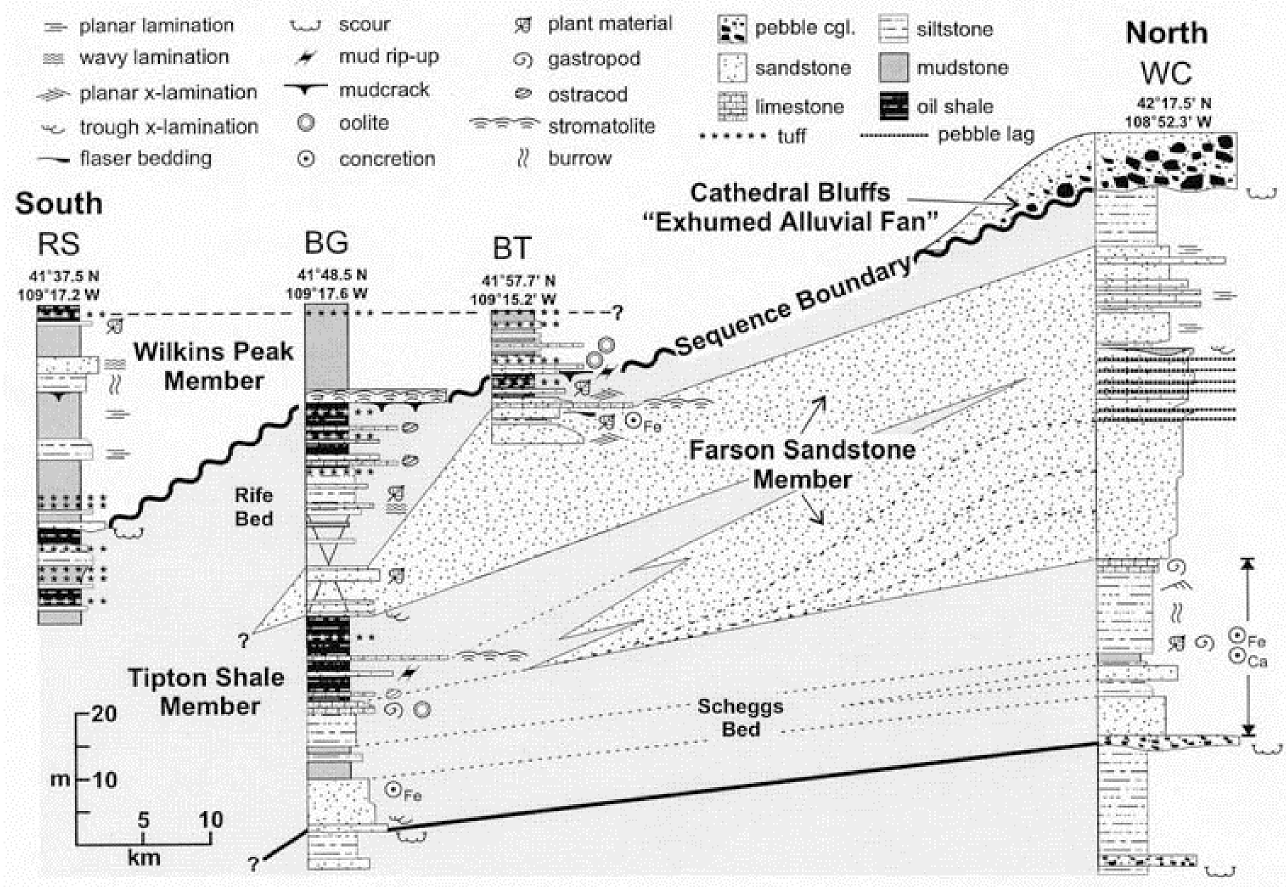


Figure 24: Correlation of measured sections of the Tipton Shale and Wilkins Peak Members of the Green river Formation across the central Green River Basin. See figure 16 for locations of sections. Section BT (Boar's Tusk) corresponds to the Day 2 field trip stop. (Pietras et. al., 2003).

Day 3:

- Hell's Half Acre & Casper Arch
- Uranium – Smith Ranch-Highlands Mine

Lander to Hell's Half Acre Roadside Geology

Today's route backtracks through Riverton and Shoshoni then follows U.S. Highway 26 eastward across the central and eastern Wind River Basin through the small town of Moneta, along Poison Creek, then onward to the eastern margin of the Wind River Basin . From Shoshoni to Hell's Half Acre, the Eocene Wind River Formation is poorly exposed on basin floor. The Rattlesnake Hills are visible to the south, the Owl Creek Mountains to the north, and the Casper Arch gently rises to the east.

The Rattlesnake Hills partially expose an Archean greenstone belt, similar to the bedrock at South Pass that was intruded during the Eocene by alkaline volcanic rocks (Hausel, 1996). Gold was discovered there in 1982 and lead to exploration by several companies that has delineated at least one deposit containing more than one million ounces of disseminated low-grade gold. Gold is hosted by both Archean and Eocene rocks. Exploration activity is on-going.

Sand Dunes

An east-west trending complex of sand dunes extends from Shoshoni across the Wind River Basin and Casper Arch to the city of Casper. To the east, the Casper Arch acts as a natural funnel for prevailing westerly winds as it forms a topographic low between the Bighorn Mountains to the north and the Laramie Range to the south. The dunes appear to have formed around 12,000 to 19,000 years ago. Many are dormant and in the processes of being reclaimed by prairie grasses and others are still active and migrating east. These dunes likely originated after the end of recent Pinedale glaciation about 15,000 years ago when melting glaciers liberated large quantities of sediment for water and wind to transport.

Hell's Half Acre

This unique landscape marks western side of Casper Arch and eastern margin of the Wind River Basin. On the east side of Hell's Half Acre, Upper Cretaceous Lance Formation (buff sandstone, greenish shale) and the Paleocene Fort Union Formation (brown & gray sandstone, gray shale, thin coal) dip very steep to the west. On western side of chasm pink, red and yellow claystone and sandstone of the Eocene Wind River formation dip gently west and unconformably overly the Fort Union and Lance Formations (Figure 25).

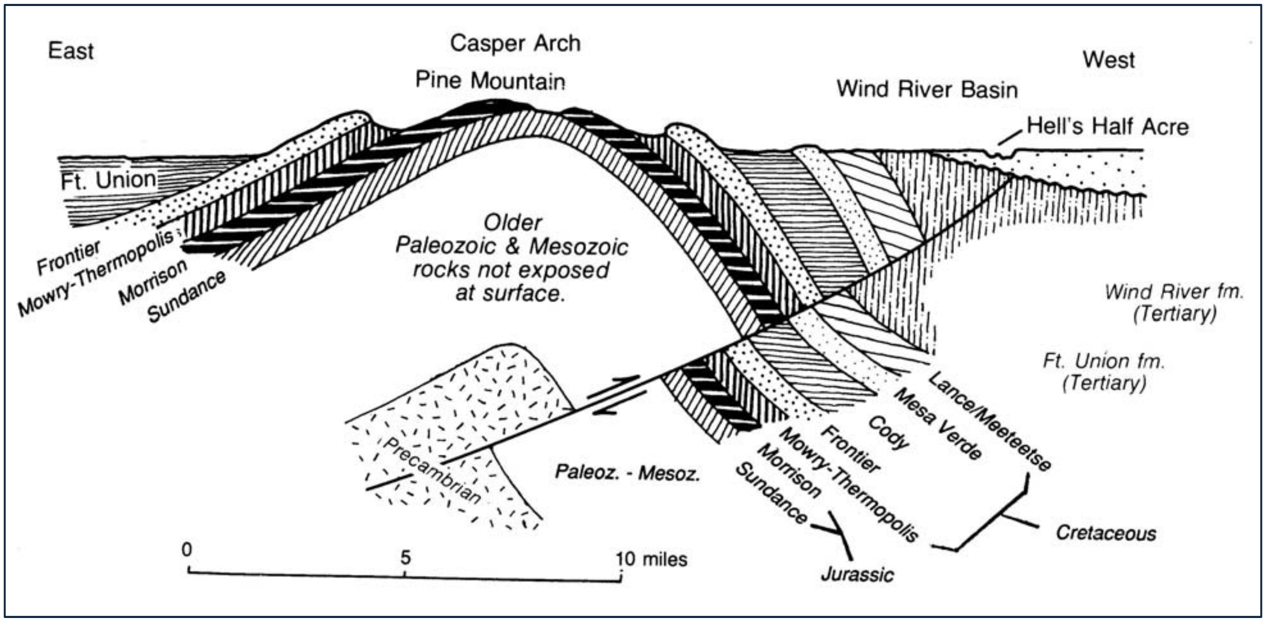


Figure 25: Structural cross section of the Pine Mountain Dome and geologic relationships at Hell's Half Acre (Lageson and Spearing, 1988)

Hell's Half Acre to Casper Roadside Geology

This highway segment traverses the northwest-southeast trending Casper Arch. The Casper Arch is a large, thrust-faulted, Laramide anticline between the Wind River and Powder River basins. The arch is asymmetric with steeply dipping beds on the western flank and more gently dips on the eastern flank (see cross section on geologic highway map of Wyoming). Surface outcrops are poor and are dominated by Upper Cretaceous Cody Shale.

A large northeast dipping thrust fault, the Casper Arch fault, has thrown Precambrian rocks and their overlying sediments westward over Mesozoic and older rocks of the eastern Wind River Basin. This structural interpretation is supported by seismic reflection and drilling. In 1980 oil drilling penetrated almost 9,000 feet of Precambrian granite before crossing the Casper Arch fault and drilling to a 20,000 feet total depth and completing a gas well in the Cretaceous Frontier Formation.

Pine Mountain Dome

This classic structural dome is visible to the south between Powder River and Natrona. It is flanked by Cretaceous strata and exposes Jurassic Morrison and Sundance Formations in the core. Oil and gas has been produced from this classic dome trap. Salt Creek/Teapot Dome, Poison Spider, and Tisdale Mountain anticlines, which expose older Cretaceous rocks in their cores, are other important oil fields located within the Casper Arch.

Emigrant Gap Anticline

Between Natrona and Casper, the Emigrant Gap anticline is visible to the south and is outlined by steep dipping Frontier Formation.

Casper to Smith Ranch-Highland Mine Roadside Geology

Approaching Casper from the northwest along U.S. highway 26/20, Casper Mountain begins to dominate the view to the southeast. Casper Mountain is a Laramide uplift and marks the northern end of the Laramie Range (Figure 26).

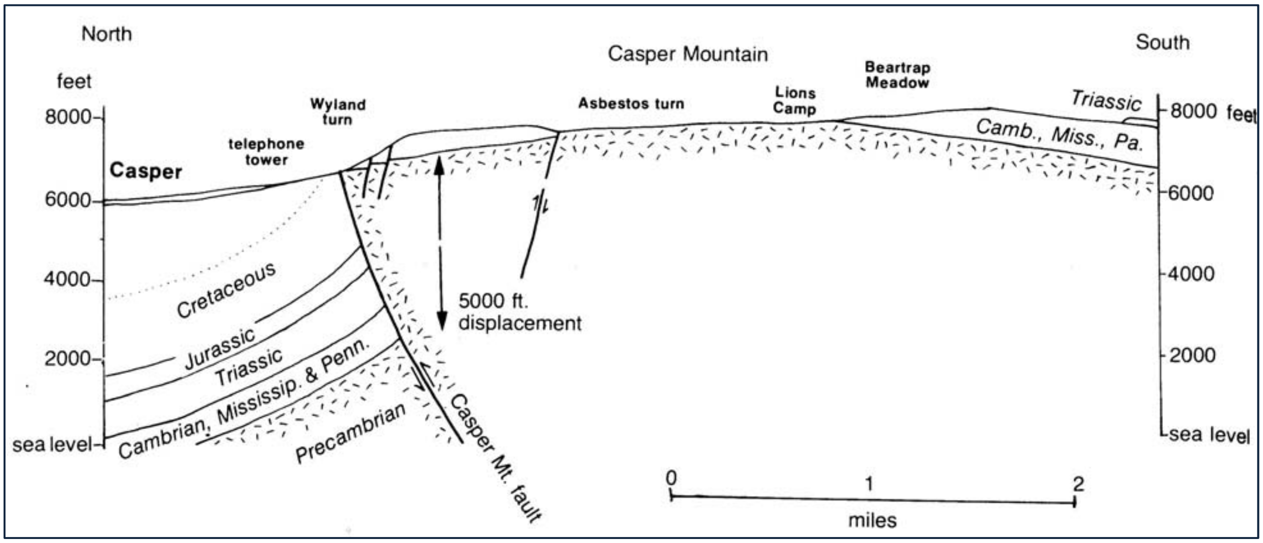


Figure 26: North-south structural cross section of Casper Mountian (Lageson and Spearing, 1988)

Interstate 25 follows the Platte River from Casper to Glenrock. To the south, the view is framed by Casper Mountain and the Laramie Range. Bedrock units are Cretaceous sedimentary rocks.

The Glenrock oil field has produced nearly 3 million barrels of oil from lower Cretaceous rocks since its discovery in 1949.

The Dave Johnston Power Plant, operated by Pacificorp, is visible along the Platte River about six miles east and downstream of Glenrock.

Day 3 Energy Industry Site Visit - *In-Situ* Recovery Uranium Mine and Mill

Cameco produces uranium via in-situ recovery (ISR) methods from sandstone roll-fronts (Figure 27).

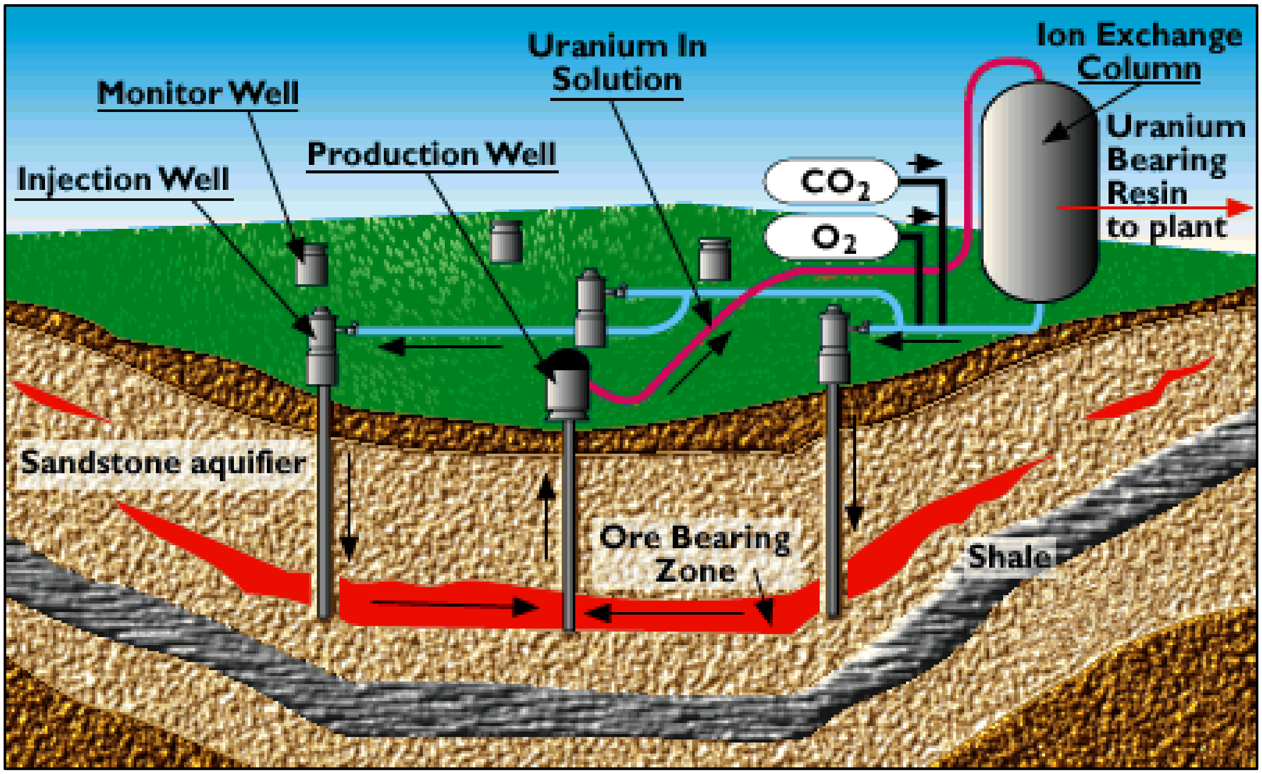


Figure 27: Uranium *in-situ* recovery (ISR) method employed at Cameco's Smith Ranch/Highlands project (Cameco Resources, 2011).

Smith Ranch-Highland Mine to Newcastle, Wyoming Roadside Geology

From Cameco's Smith Ranch-Highland Mine to Bill, Wyoming and northward to Wright, the field trip route follows Wyoming Highway 59 through the Powder River Basin over Wasatch Formation sandstone, siltstone, and mudstone.

South of Wright, the field trip route turns east to follow Wyoming Highway 450 to Newcastle. After about nine miles, the highway passes into the Paleocene Fort Union Formation and the Black Thunder and Jacobs Ranch coal mines. The Black Thunder Coal Mine, operated by Arch Coal and the largest coal mine in the U.S., produces coal from the Tongue River Member of the Paleocene Fort Union Formation. The Fort Union Formation is discussed in more detail in Day 5 field trip guidebook materials.

West of the Black Thunder Mine, the highway passes through the Rochelle Hills which expose Fort Union Formation with extensive clinker. A discussion of clinker is included in the Day 5 field guide materials.

Approximately thirty-eight miles east from the junction of Wyoming Highway 59 and 450, Upper Cretaceous Lance Formation is encountered. The Lance Formation in eastern Wyoming is known for yielding dinosaur fossils such as *Triceratops*, *Pachycephalosaurus*, and *Tyrannosaurus*. Casper College has recently begun excavation of what they believe to be a nearly complete Tyrannosaurus specimen from the Lance Formation near Lusk, Wyoming. From here to Newcastle, progressively older, gently west dipping Cretaceous strata are encountered as the highway traverses the western edge of the Powder River Basin. While the Upper Cretaceous section along this stretch of highway is dominated by the Pierre Shale, prominent resistant hogbacks encountered include, from east to west, Fox Hills Sandstone and impure chalk and sandstone of the Niobrara Formation. The highway also passes through the Mush Creek and Skull Creek oil fields which produce from sandstone of the Newcastle Formation at depths in excess of 4,000 feet. Newcastle, Wyoming sits upon the Cretaceous Mowry and Belle Fouche formations and is flanked to the east by hogbacks of Newcastle Formation sandstone and to the west by hogbacks composed of limestone of the Greenhorn Formation, both of Cretaceous age. The Newcastle Formation and oil fields of the region will be discussed during the Osage oil field stop on Day 4 of the field trip.

Day 4:

- Osage Oil Field
- Bear Lodge Mountains Rare Earth Element District

Newcastle to Osage Roadside Geology

U.S. Highway 16 north of Newcastle to Osage and then Upton, more or less follows the strike of Late Cretaceous Belle Fouche Shale tilted dipping gently southwest along the western flank of the Black Hills uplift. The long swale that the highway follows is bounded to the west by the Cretaceous Greenhorn Formation, and the east by hogbacks comprised of sandstone from the Newcastle Formation and Cloverly Formations further to the east. The swale is underlain the Cretaceous shale of the Mowry Formation and Cody Shale.

The Osage Oil Field

The Osage oil field, located about fifteen miles north of Newcastle, Wyoming, produces from the stratigraphic traps within the Cretaceous Newcastle Formation. The Newcastle Formation along the eastern edge of the Powder River Basin is interpreted as alluvial and estuarine deposits filling channels incised into the underlying marine Skull Creek Shale (Stone, 1972). Oil seeps along the western front of the Black Hills spurred booms between 1885 and 1900. But in 1919, discovery of high-grade crude oil in commercial quantities adjacent to a railroad initiated development of the Osage oil field. Figure 28 shows a representative stratigraphic section and well log for the Newcastle Formation within the Osage oil field.

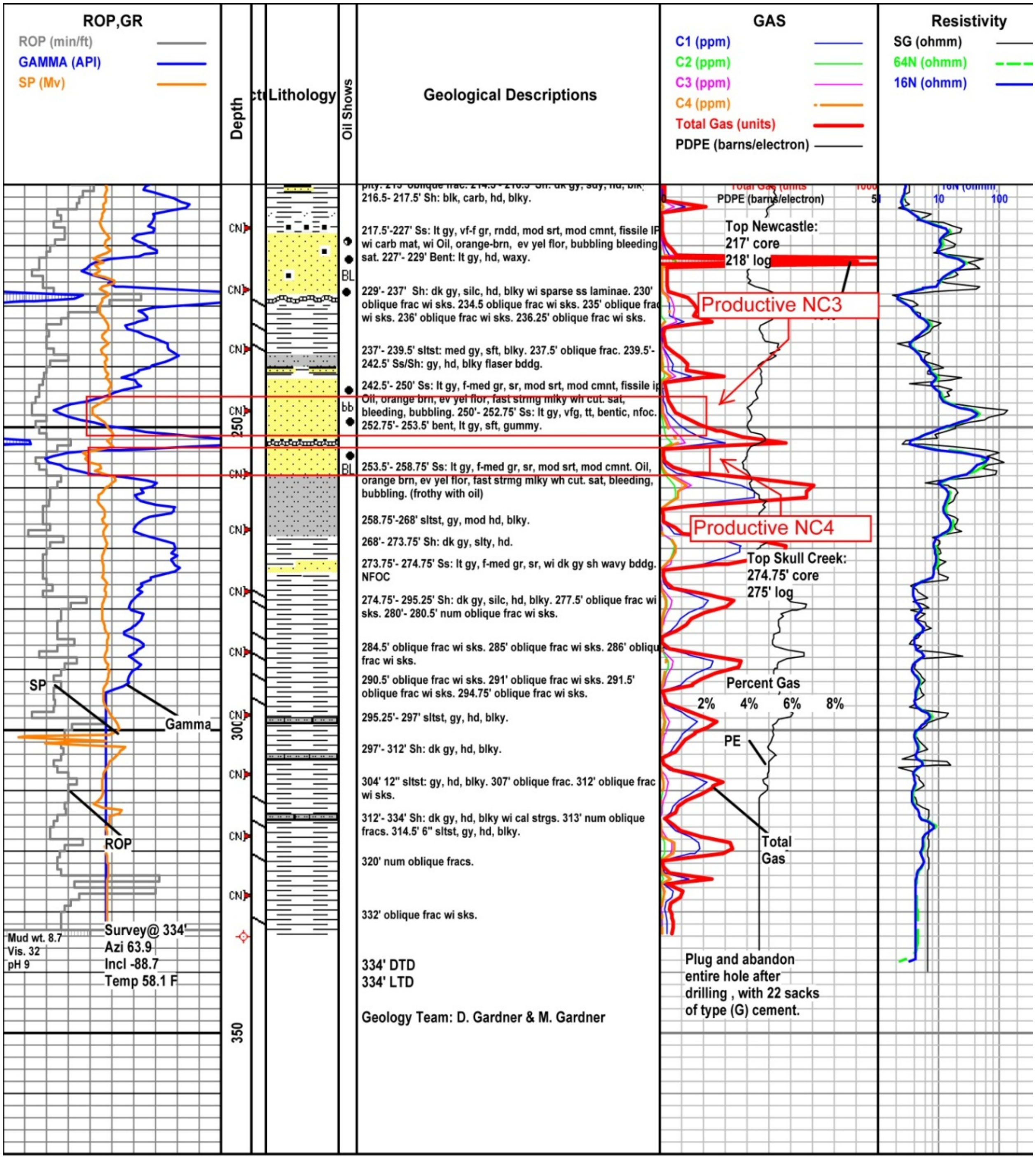


Figure 28 : Representative stratigraphic section and well log of the Newcastle Formation in the Osage oil field, Wyoming (RockWell Petroleum, 2007)

Other oil fields in Weston County, Wyoming that also produce from the Newcastle Formation include the Fiddler Creek and Fiddler Creek East, both west of the Osage field, and the Clareton, Mush Creek, and Skull Creek fields southwest of Newcastle, Wyoming (Figure 29).

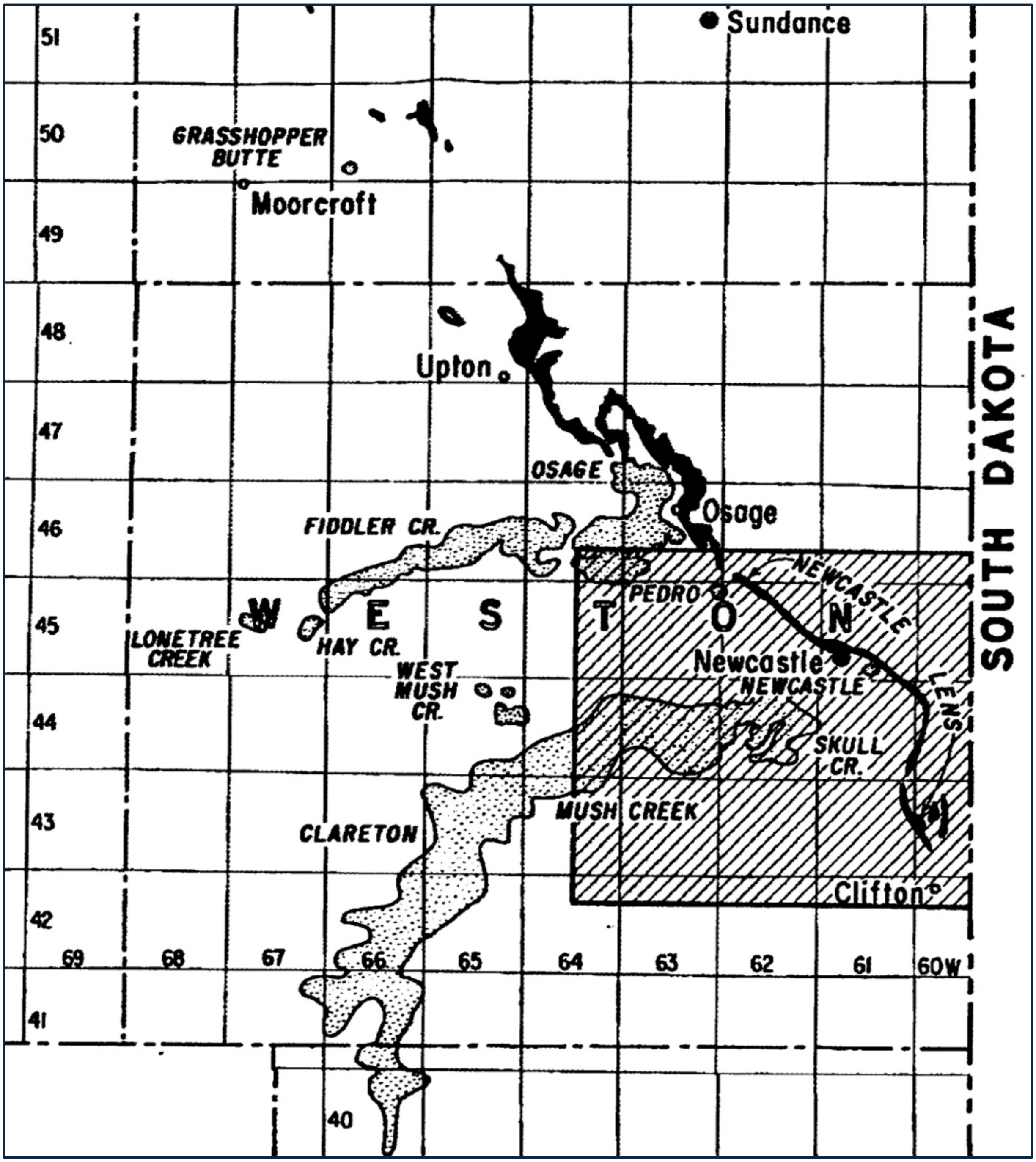


Figure 29 : Oil fields of eastern Weston County, Wyoming. Stipled areas indicate oil fields that produce primarily from the Newcastle Formation; black indicates surface outcrops of the Newcastle Formation (Baker, 1962)

Cumulative production from these six fields is nearly 100 million barrels of oil (Wyoming Oil and Gas Conservation Commission, 2011). Oil production from the Osage field has declined from a peak of about 750,000 barrels of oil in 1978, when the Wyoming Oil and Gas Conservation Commission began collecting records to a 2010 production of about 50,000 barrels of oil.

Enhanced oil recovery techniques such as water, polymer, and carbon dioxide flooding have been conducted in the area with variable success.

In 2007 RockWell Petroleum (RWP), a Sheridan-based, non-conventional oil production company began construction of an oil mine within the Osage oil field following the modest success of its Greybull, Wyoming oil mine. RWP sought to recover stranded oil, thought to comprise up to 60-90% of the original oil in place, by mining beneath the oil reservoir then drilling numerous wells on a two hundred foot spacing to allow gravity drainage of the remaining stranded oil (Figures 30, 31, and 32).

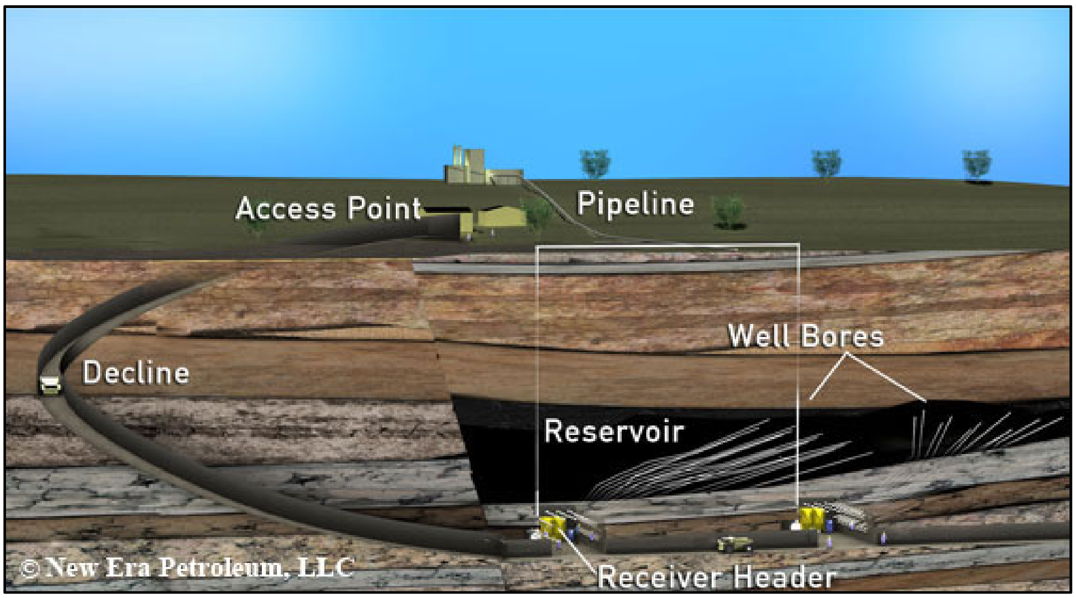


Figure 30: Illustration of underground oil mining technique (New Era Petroleum, 2011).

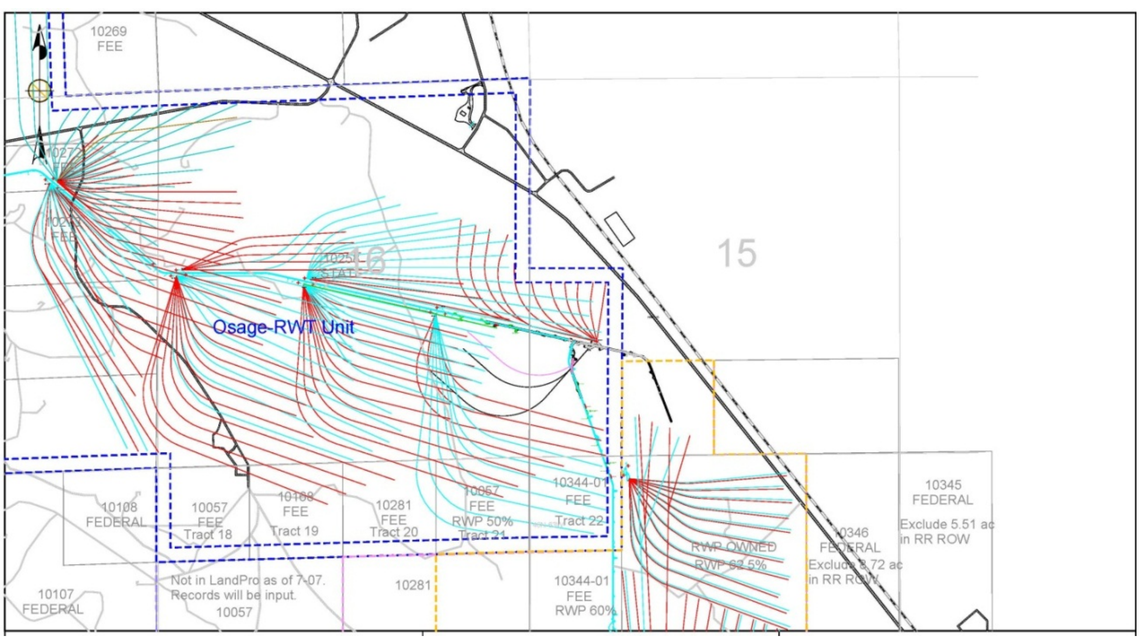


Figure 31: Conceptual single-sand horizontal well bore design for Osage oil mine (RockWell Petroleum, 2007)

Figure 32: Photo of an underground oil drilling station, Greybull Oil Mine, Greybull, WY (New Era Petroleum, 2011)

In the fall of 2008, RWP collapsed into bankruptcy, due in part to poor production from its Osage oil mine project which made securing additional investment capital difficult. Nevertheless, the Osage oil mine project provided many valuable lessons particularly with regard to proper oil field selection for future underground oil mine projects. New Era Petroleum, also a Sheridan-based company, has picked up where RockWell Petroleum stopped and is currently in the process of creating a rigorous oil field selection model for future underground oil mining projects.

Upton to Sundance Roadside Geology

At Upton, the field trip route turns northwest onto Wyoming Highway 116. For thirty miles from Upton to Sundance, the highway passes over progressively older, gently southwest dipping sedimentary rocks of from Late Cretaceous to the distinctive red beds of the Triassic Spearfish Formation. The Spearfish Formation is the Black Hills equivalent of the Chugwater Formation of the rest of Wyoming. Formations in order of appearance from Upton include: Niobrara, Mowry, Newcastle, Skull Creek Shale, Cloverly, Morrison, Sundance, and Spearfish.

Black Hills Cenozoic Igneous Province

Numerous igneous intrusions and associated domes of Black Hills Cenozoic Igneous Province are visible between Upton and Sundance. Many of these intrusions are interpreted as laccoliths – mushroom shaped intrusions the dome the overlying sedimentary strata (Figure 33). Roughly sixteen miles from Upton towards Sundance along WY 119, the road crosses Inyan Kara Creek. Up the valley to the southeast is Inyan Kara Mountain, a small structural dome, about 2 miles in diameter cored by a laccolith of syenite porphyry (Mapel and Pillmore, 1963). Mississippian Pahasapa Limestone is the oldest rock unit that outcrops in the dome.

Six miles to the northeast of Inyan Kara Creek, the Black Buttes appear about five miles east of the highway (to the right for north travelers). This is another igneous intrusion.

Three miles from the Black Buttes overlook, Lime Butte, a small structural dome appears to the east (to the right for northbound travelers). Beds of Triassic Chugwater Formation dip away from a core of Permian rocks. This dome is likely cored by a laccolith that has not been exposed by erosion (Figure 33).

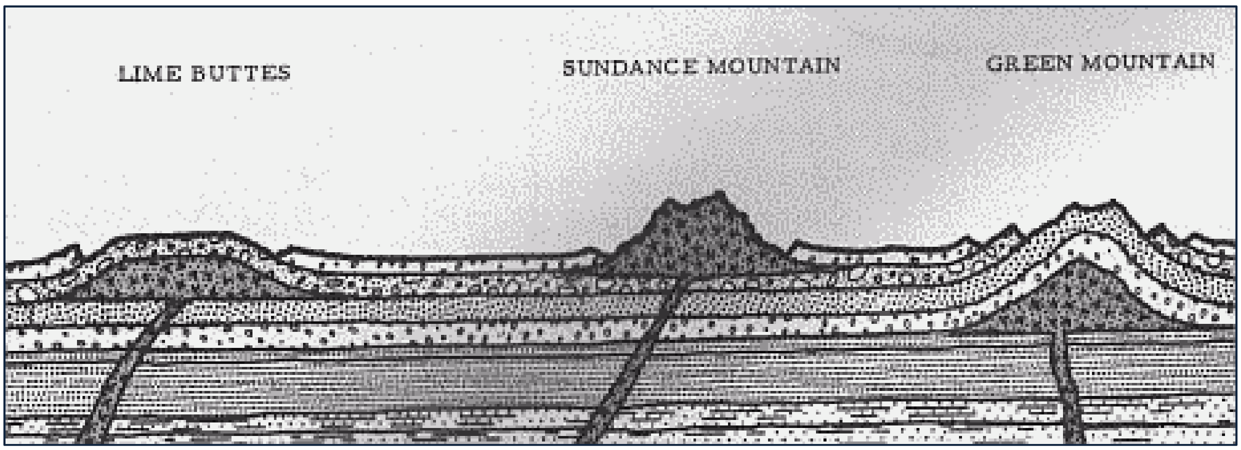


Figure 33 - Northeast to southwest cross section from Green Mountain to Lime Buttes southeast of Sundance, Wyoming. Cross section length is about 7 miles (Darton, 1909).

As WY 119 approaches Sundance from the south, Sundance Mountain becomes prominent ahead and to the north. Sundance Mountain is also known as “The Temple of the Sioux”. Here the Sioux Indians gathered yearly to conduct the sun dance in worship of the sun.

Reaching Sundance, the Bear Lodge Mountains become visible to the north. The largest igneous complex and dome of the Black Hills Cenozoic igneous province and the focus of today’s energy industry site visit, a discussion of the geology and REE mineralization in the Bear Lodge Mountains follows. Green Mountain to the east of Sundance is a small structural dome with a laccolith core.

Day 4 Energy Industry Site Visit – Rare Earth Elements

Regional Geologic Setting of the Bear Lodge Mountains

The Bear Lodge Mountains represent a small satellite structural dome located on the northwest edge of the larger Black Hills dome that formed during the Laramide Orogeny. Archean schist, gneiss, and granite outcrop in the central portion of the Bear Lodge Mountains and is flanked by titled sedimentary rocks ranging in age from Cambrian towards the core to Cretaceous along the distal flanks. Locally, these tilted sedimentary rocks are unconformably overlain by Miocene gravel and sandstone of the Ogallala Formation.

The Bear Lodge Mountains and other igneous intrusions visible south of Sundance are part of the Black Hills Cenozoic igneous complex. This west-northwest to east-southeast trending belt of alkaline igneous rocks, ranges in age from 38 to 60.5 Ma. Intrusive complexes of the Missouri Buttes and Devils Tower lie at the western end of this trend and the Bear Butte and Vanocker complexes mark the eastern end of the trend near Sturgis, South Dakota (Figure 34; Karner, 1981).

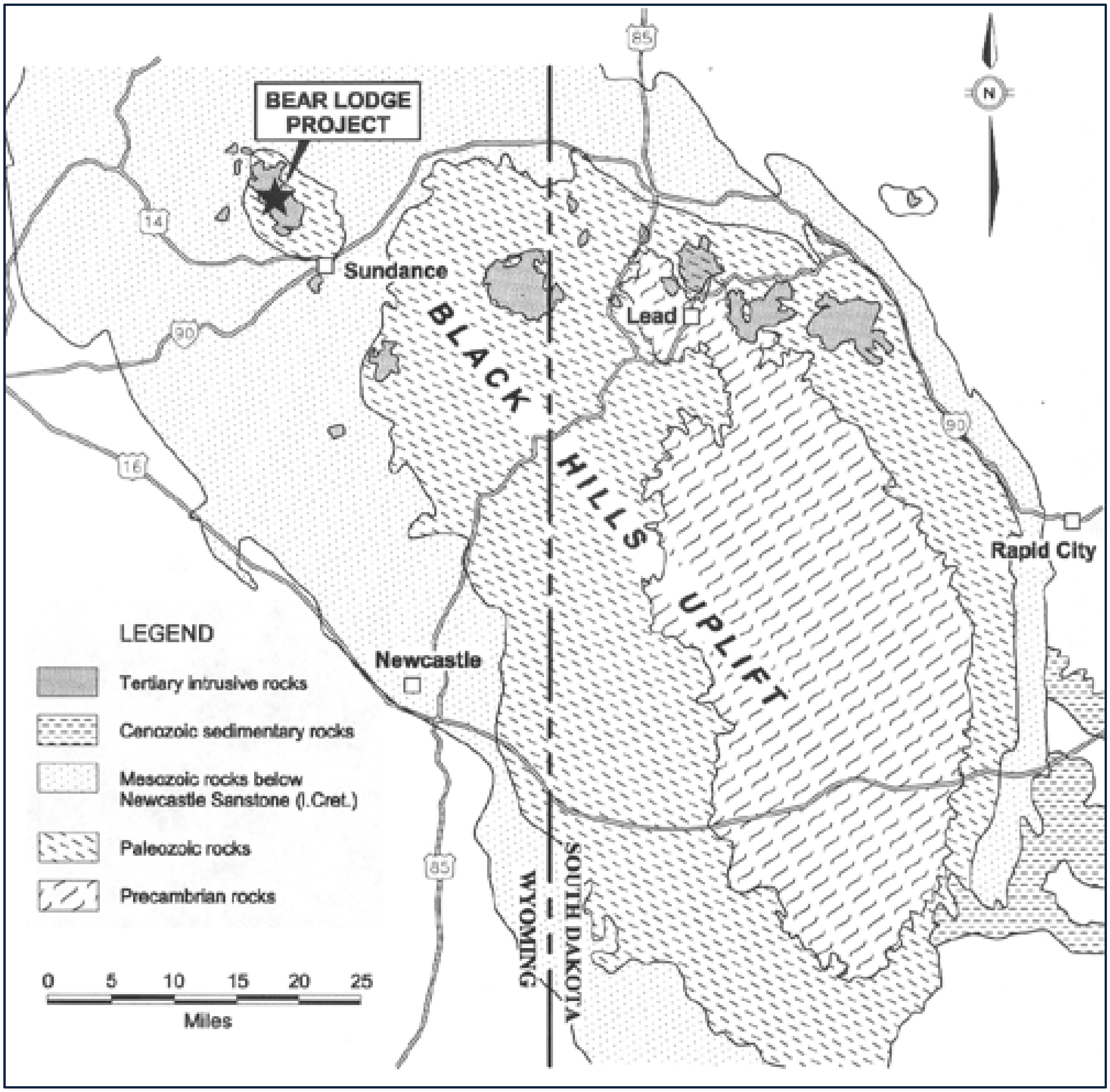


Figure 34 - Black Hills Cenozoic igneous province and location of Bear Lodge Mountains REE project.
(Rare Element Resources, 2010)

The Bear Lodge Mountains contains a trachyte-phonolite-quartz latite association of hypabyssal and volcanic igneous rocks that is cored by an excellent example of a carbonatite-pyroxenite-alkalic intrusive association (Karner, 1981; Jenner, 1984). The complex is an elongated body roughly ten by five kilometres. The late stage carbonatite activity has produced extensive rare-earth element (REE), and minor gold, and copper mineralization. This activity involved intrusion of carbonatite dikes, intrusive brecciation, potassic metasomatism (called fenitization), and hydrothermal alteration. Outcrops are poor, requiring trenching and drilling to delineate the ore bodies (Rare Element Resources, Ltd., 201

Rare Earth Element Mineralization in the Bear Lodge Mountains
Listed in order of decreasing abundance, the light REEs cerium, lanthanum, neodymium, and praseodymium are the most abundant the Bear Lodge Mountains. Other light REEs concentrated here include samarium, europium, and gadolinium. Neodymium and praseodymium are the most valuable.

Carbonatite dikes host the majority of the REE mineralization in the Bear Lodge Mountains and range from microveinlets to dikes up to 15 meters thick. Dikes dip steeply to the southwest and strike northwest-southeast. Ancylite ($Sr(REE)(CO_3)_2(OH)(H_2O)$), and Bastnaesite, $(REE)CO_3(F,OH)$ are the main minerals that host REEs and their abundances in the carbonatites range from trace levels to greater than 50% by volume. Other REE-bearing minerals include synchysite [$Ca(REE)(CO_3)_2F$], parisite [$Ca(REE)_2(CO_3)_3F_2$], and cerianite [$(CeTh)O_2$]. Two distinct types of carbonatite are recognized in the Bear Lodge Mountains: sovite carbonatite and silicocarbonatite.

Fine to coarse crystalline calcite characterize sovite carbonatite. Accessory minerals include biotite, potassium feldspar, augite, strontianite, dolomite, and various sulfide and oxide minerals. With abundances ranging from a trace to 30% by volume, the sulfide minerals include pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, molybdenite, and the oxide minerals include hematite, rutile and ilmenite.

The silicate minerals biotite/phlogopite and potassium feldspar dominate silicocarbonatite with abundances ranging from 50 – 75 % by volume. Calcite and the accessory minerals aegirine, apatite, strontianite, barite, and celestite also occur in these rocks. Sulfide minerals such as pyrite, pyrrhotite, chalcopyrite, galena, sphalerite and the oxide minerals hematite and rutile range from trace amounts to almost 25% by volume. Sovitic carbonatite cores are common within silicocarbonatite dikes that are over 5 meters thick.

Iron-manganese (FMR) veins, dikes and stockworks also host REE mineralization in the Bear Lodge Mountains. While not as common, FMR veins generally have a higher concentration of REE than carbonatite. FMR bodies have been interpreted as the altered oxidized equivalents of a carbonatite. Ore minerals include bastnaesite ($(REE)CO_3(F,OH)$) , and occasionally monazite [$(REE,Nd)PO_4$].

Day 5:

- Dry Fork Station & Coal Mine
- Powder River Basin Coal Bed Methane

Sundance to Gillette Roadside Geology

From Sundance to Gillette along U.S. Interstate 90 west descends the western flank of the Black Hills uplift, into the central Powder River Basin, passing over a complete, but poorly exposed, gently west dipping, section of progressively younger strata from Jurassic strata in Sundance to Eocene strata of the Wasatch Formation in Gillette.

Devils Tower

Between Sundance and Moorcroft Devils Tower is visible to the northwest. Rising about 1,200 feet above the Belle Fouche River, Devils Tower is the remnant of a phonolite porphyry volcanic neck. The presence of an elliptical knoll of autobreccia is located northwest of the tower and is evidence for its origin as a volcanic neck. Devils Tower and nearby Missouri Buttes, dated at 40 and 50 Ma, respectively, are the western most igneous occurrences of the Black Hills Cenozoic igneous province (Halvorson, 1980).

Moorcroft

The town of Moorcroft rests on the Upper Cretaceous Lance Formation. The thick-bedded, buff-colored sandstone and greenish shale of the Lance Formation represent fluvial sediments that filled the receding Western Interior Cretaceous Seaway.

The contact between the Cretaceous Lance Formation and the Fort Union Formation lies poorly exposed between Moorcroft and Rozet to the west.

Rozet Oil Field

First discovered in 1959, the Rozet oil field produces from the Cretaceous Muddy Sandstone which is equivalent to the Newcastle Formation and the Pennsylvannian Minnelusa Formation (Ryder et. al., 1981). Wells range from 8,000 – 9,000 feet deep. Yearly production has declined from over 700,000 barrels of oil in 1978 to 98,000 barrels of oil in 2010 (Wyoming Oil and Gas Conservation Commission, 2011).

Wyodak Coal Mine

Owned and operated by Black Hills Corporation is the oldest operating coal mine in the U.S. began in the 1918 as the Peerless Mine – an underground room-and-pillar coal mine. The current Wyodak strip mine began in 1923 to provide power for the Homestake Gold Mine in Lead, South Dakota.

In the 1950s, the Wyodak mine stripped the overburden and mined through the pillars of coal left in the by the old Peerless Mine workings.

The mine employs over one hundred people and produces about six million tons of coal per year from the Wyodak coal seam of the Tongue River Member of the Paleocene Fort Union Formation (discussed below). About two million tons are consumed yearly in the adjacent Wyodak Power Plant.

With reserves of about 274 million tons, the mine has a 42 year life at current production. A 12.5% and 9% royalty is paid based on four federal leases and one state lease (Black Hills Corporation, 2011).

As is the case with most western Power River Basin coal mines, the contact between the Tongue River member of Fort Union Formation and the Wasatch formation is just a few miles to the west of the mine.

Wyodak Power Plant

When it went into operation in 1978, Wyodak was the world's largest air-cooled coal-fired power plant. It is a joint venture between Pacific Corp. (80%) and Black Hills Corp. (20%).

Clinker in the Powder River Basin

Near the Wyodak Mine and Power Plant, reddish, erosion resistance clinker deposits cap numerous hills and buttes. Clinker is the term for the rocks that have been altered by the heat from a coal bed fire and is derived from the same term used to describe brick that has been overcooked in a kiln. Coal seams are ignited by either lightning strikes, prairie wild fires, or the spontaneous combustion due to heat of wetting coal and oxidation of pyrite and marcasite (a low temperature polymorph of pyrite). Over the past several million years, many intermittent coal fires have burned throughout the Powder River Basin. Coal fires begin at an outcrop then spread along the outcrop and progressively inward. The hot gases associated with these fires alter the overlying rock producing the red clinker.

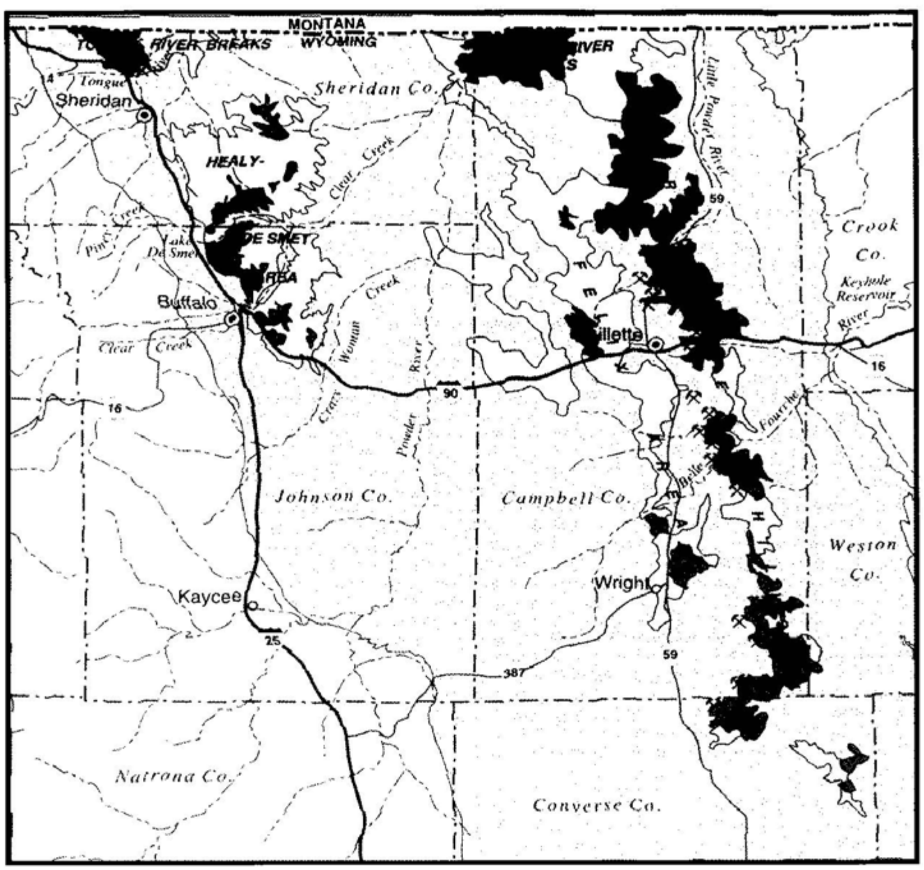


Figure 35: Clinker outcrops in the Powder River Basin (Coates and Heffern, 1999)

Clinker is common through the Powder River Basin (Figure 35) and represents some 30 billion tons of combusted coal. Native Americans named the Powder River for this distinctive red rock, calling it, *Wa Ha Sah*, meaning red stone. On William Clark's 1806 return route down the Yellowstone River in Montana, he observed the clinker in the gravels at the confluence of the Yellowstone and Powder rivers and also named it the Redstone River.

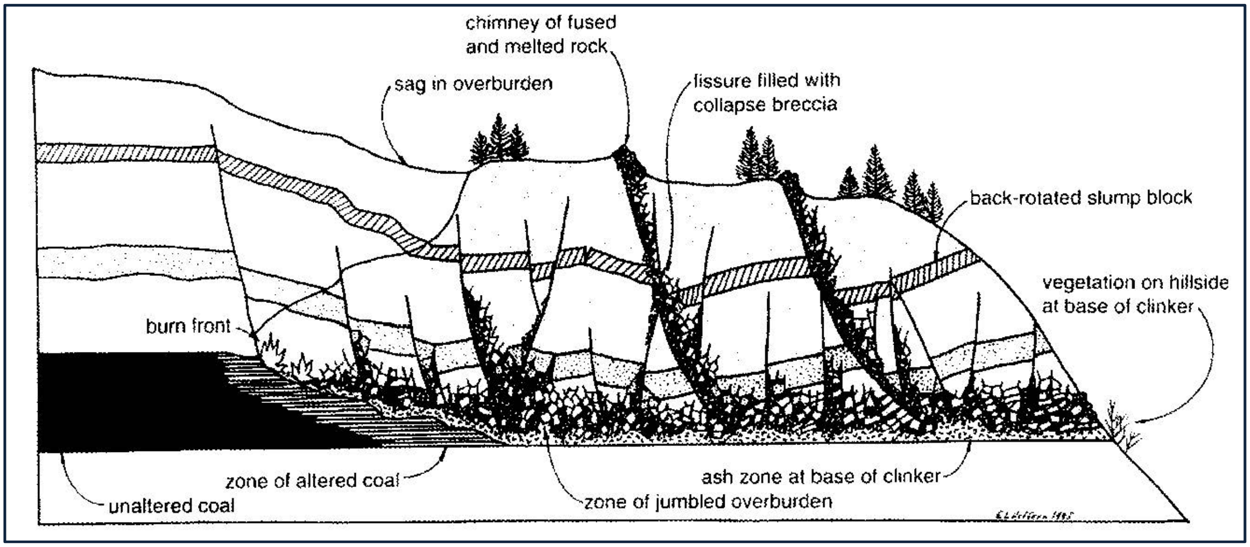


Figure 36: Idealized cross section of a clinker deposit (Coates and Heffern, 1999)

Figure 36 illustrates a cross section of a clinker hillside. As the burn front advances into the hillside and the underlying coal is combusted, the overlying rocks subside along small faults in a series of back-rotated slump blocks. Some of these fracture zones are filled with collapse breccia. Slumping results in a topographic sag overlying the burn front and at the contact between altered and unaltered overburden (Figures 36 & 37). These fractures allow air to move to the burn front and combustion gases to vent to the surface. Heat is transferred upward by this fracture-enhanced convection. Clinker only forms above the burning coal. Conductive heating only extends less than two feet below the coal bed.

Clinker is a highly variable suite of thermal metamorphic rocks. The variation in rock types typical of clinker occurrences is due to three factors. First, grain size and mineralogy of the parent sedimentary rock is variable. Mudstone, shale, siltstone, and sandstone are common in the Wasatch and Fort Union Formations and are potential parent rocks of clinker. The second and third factors are variable degrees of heating and variable degrees of oxidation or reduction during and/or after heating.

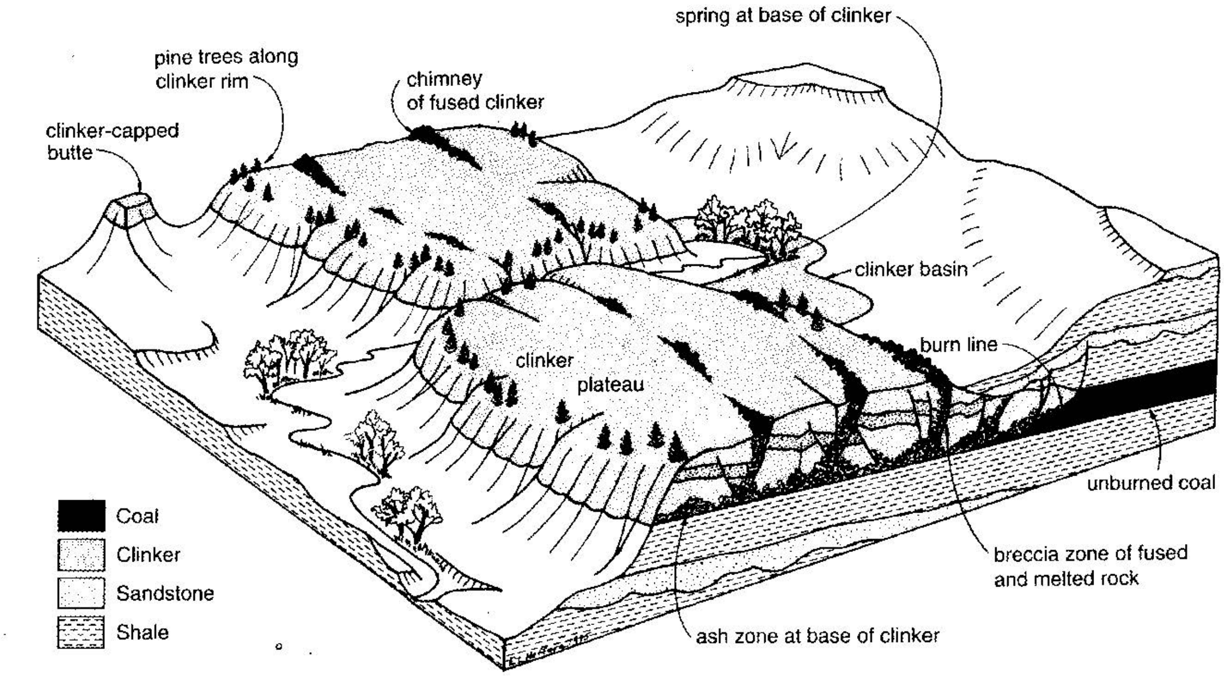


Figure 37: Idealized geomorphology of a Powder River Basin clinker deposit (Coates and Heffern, 1999)

Rusty red hematite and ochre limonite dominate most clinker deposits and result from oxidation during or shortly after heating. Calcite-rich parent rocks turn yellow. Fractures also develop during the formation of clinker.

At the base of the clinker, in the ash layer, and in fractures above the base, where reducing condition exists, black and grey rocks form. This reducing environment results from incomplete combustion. Combustion of coal underground involves the oxidation of carbon in the presence of water and restricted oxygen supply. The heat dissociates water and the oxygen reacts with carbon. Thus carbon monoxide and hydrogen gas, both excellent reducing agents, are the main combustion gases. Iron is reduced to from the minerals wüstite (iron(II) oxide, FeO) and magnetite (iron(II,III) oxide, Fe_3O_4).

Porcellanite is formed when shale or siltstone is intensely heated to near its melting point and sintered. Recrystallization occurs and a ceramic texture develops. Native Americans extensively utilized porcellanite for tools.

Paralava, the melted phase of clinker that is locally and incorrectly refered to as 'scoria', forms in association with the fracture zones that exhaust combustion gases (Figures 36 & 37). When the heated exhaust gases combine with enough air, it may burn like a blast furnace. Coates and Hefferin (1999) describe an account of this phenomenon that was observed by a Wyoming rancher in the 1930s who claimed the fire sounded "like a freight train – a roar we could hear a half mile away". Such exhalations produce near vertical, tabular chimneys of sintered and welded breccia and paralava. Paralava exhibits ropy and vesicular textures reminiscent of pahoehoe lava. These chimneys stand in relief above the less-resistant clinker after weathering and erosion (Figures 36 & 37).

Fort Union Formation

Coal Resources

Powder River Basin (PRB) coal is mined from the Tongue River Member of the Fort Union Formation. The Tongue River Member is the upper most member of the Fort Union Formation. For this reason, the majority of the coal mines line along the contact between the Fort Union Formation and overlying Wasatch Formation (Figure 38). Numerous coal beds occur in the Tongue River Member (Figure 39). The Wyodak-Anderson coal zone is the most important with an estimated reserve of about 550 billion short tons (Ellis et. al., 1999). Wyodak-Anderson coal generally yields 8,000 – 8,800 btu/lb. This is much lower than the energy yield of higher rank coals such as bituminous (~11,500 btu/lb.) and anthracite (~12,700 btu/lb.) coals.

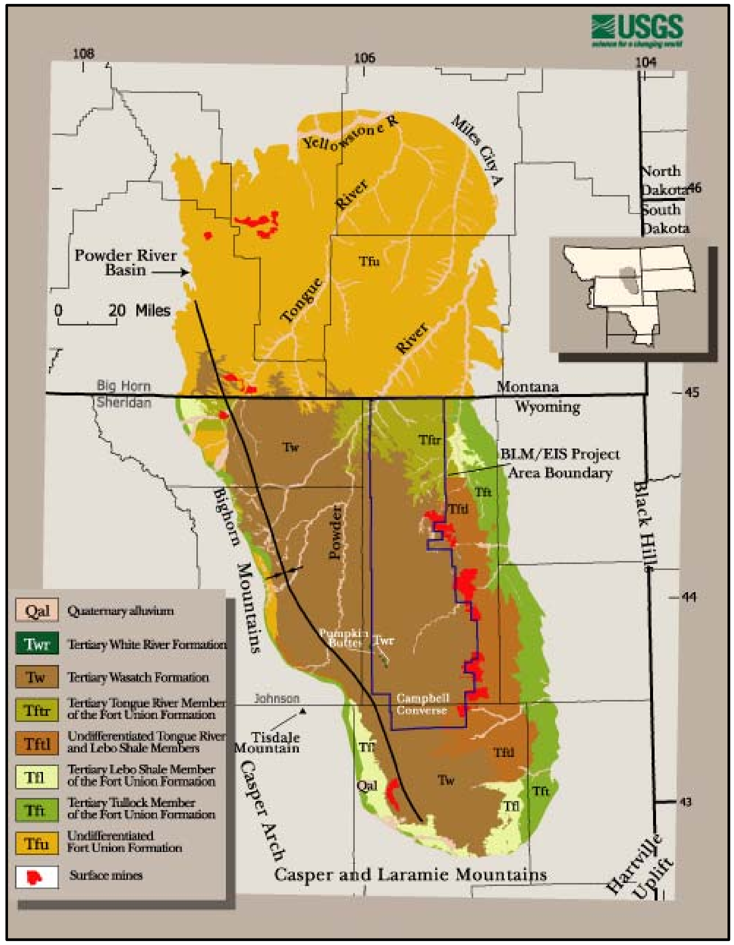


Figure 38: Tertiary geology of the Powder River Basin (Flores et. al., 2001)

With implementation of phase two of the 1990 Clean Air Act Amendments in 2000, the low sulfur dioxide content of this coal makes it a fuel of choice for coal-fired power plants throughout the United States. Other benefits of PRB coal include low ash and contents of trace elements of environmental concern.

A complex zone, individual beds within the Wyodak-Anderson coal zone split and merge throughout the PRB. This zone may split into two to eleven beds. The composite thickness of the zone may exceed 200 feet in places and is at least 50 feet thick in the majority of the PRB (Figure 40). The Wyodak-Anderson coal zone has also been the most productive coal bed methane reservoir of the PRB. Coal bed methane in the PRB is discussed in a separate section of the field trip guidebook.

Stratigraphy and Depositional Environment
The Paleocene Fort Union Formation is over 5200 feet thick along the basin axis in the western part of the Powder River Basin (PRB). Three members are recognized in ascending stratigraphic order: Tullock, Lebo, and Tongue River members (Figure 38). The Tullock Member, up to 740 feet thick, is characterized by drab yellow to light-gray sandstone and thin to thick coal beds. Drab-gray mudstone, carbonaceous shale and sparse, very thin coal beds characterize the Lebo Member. The Lebo Member ranges from 370 feet thick in the eastern PRB to 2,600 feet thick in the western PRB. The Tongue River Member, reaching a thickness of over 1,800 feet, contains thick coal beds and drab yellow to light-gray sandstone (Flores, 1999).

Floral assemblages, including palms and birches, and leaf characteristics (e.g., sizes and margins), suggest deposition of Fort Union sediments in a warm tropical-subtropical, terrestrial environment (Brown, 1958 and Nichols et. al., 1989). These workers estimate mean annual temperatures and precipitation of about 68^{o} F and 90.6 inches, respectively.

The Tullock and Tongue River members record a Paleocene fluvial system that drained the Powder River Basin and flowed northeast into the Cannonball Sea of North Dakota. The Cannonball Sea is the remnant of the more extensive Western Interior Cretaceous Seaway. Thick sandstone bodies are interpreted as meandering and anastomosed river channel deposits. Floodplain crevasse splay deposits are indicated by thin sandstones and siltstones bodies interbedded amongst overbank mudstones and backswamp coal and carbonaceous shale.

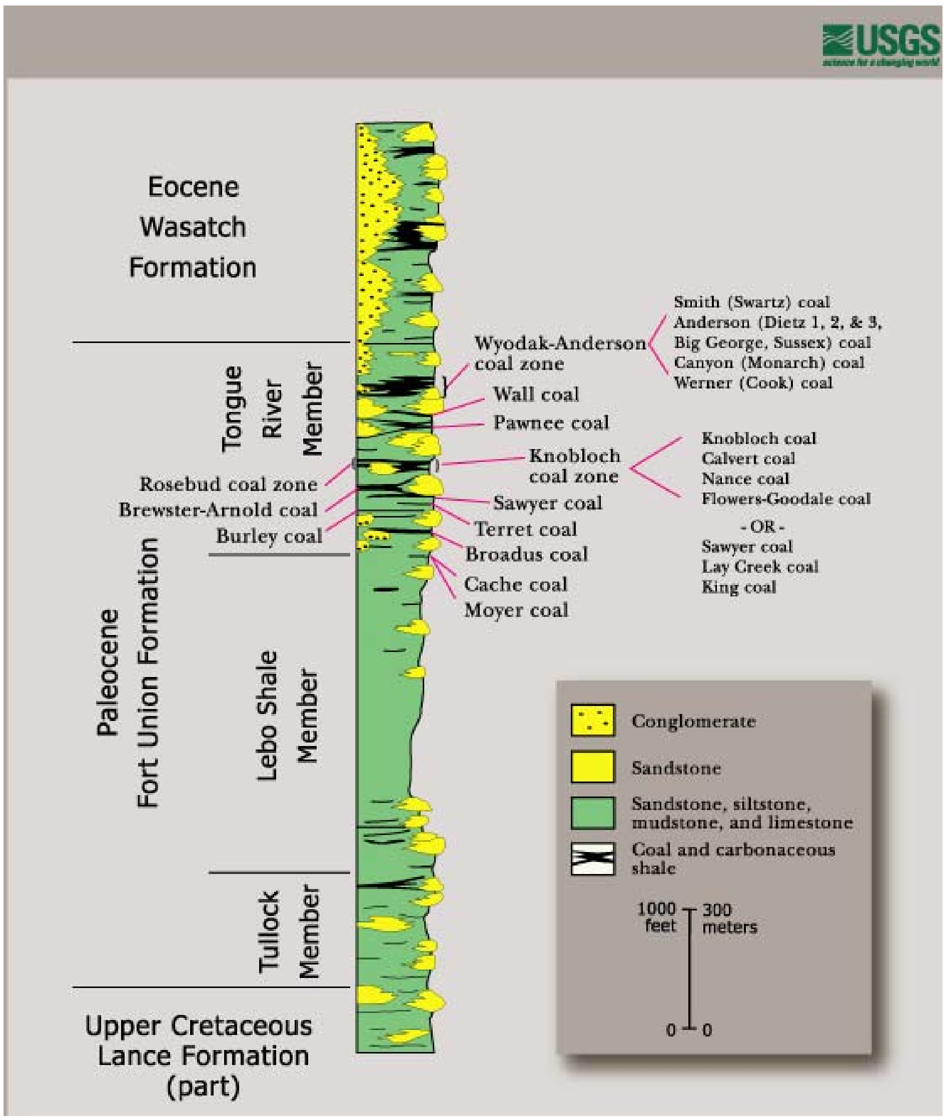


Figure 39: Stratigraphy of the Fort Union and Wasatch Formation in the Powder River Basin (Flores et. al., 2001)

On-going uplift of the Bighorn Mountains is indicated by occasional conglomerate deposited in alluvial fans and braided streams (Flores, 1999). Figure 41 is an idealized depositional model of the type of fluvial system that deposited the Tongue River and Tullock members. Fluvial deposition was interrupted by lacustrine deposition recorded by the Lebo Member (Ayers and Kaiser, 1984).

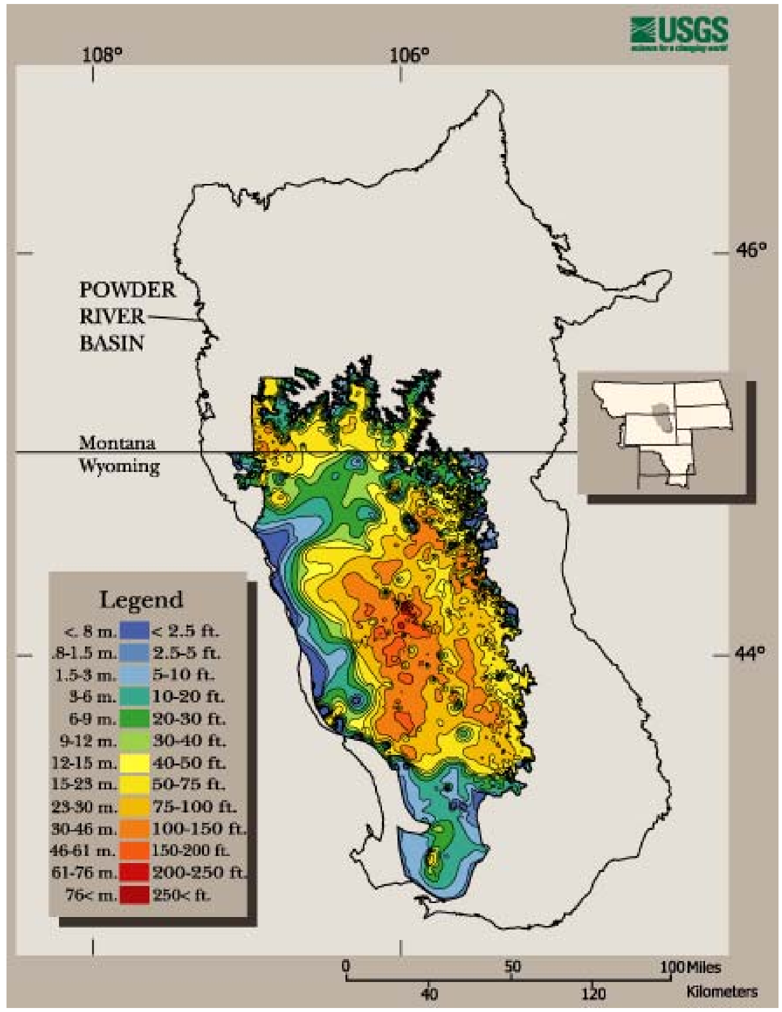


Figure 40: Thickness of Wyodak-Anderson coal zone (Flores et. al., 2001)

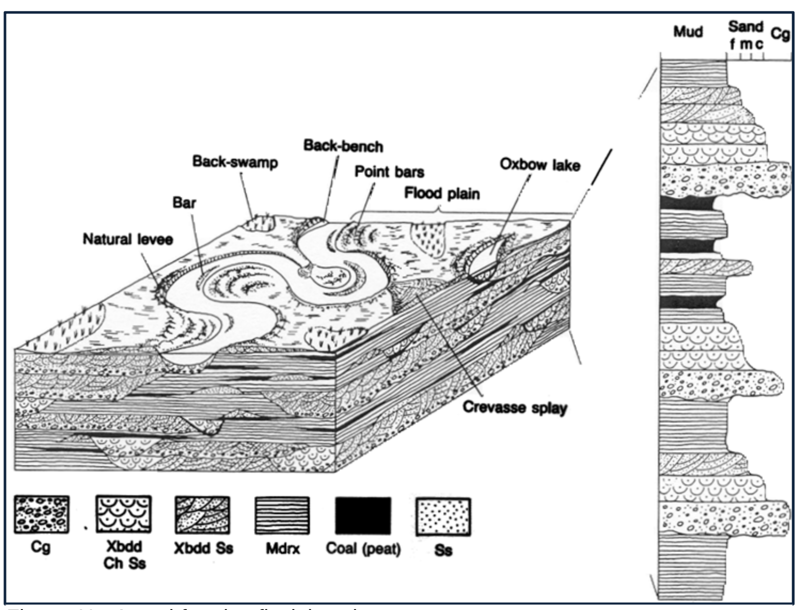


Figure 41: A coal-forming fluvial environment

Coal Bed Methane
As the field trip route traverses the Powder River Basin (PRB), numerous coal bed methane (CBM) wells can be observed. These are identified by the small box structures that encase the well head assembly (insert photo) The following section overviews the origin of coal bed methane, production history in the PRB, production techniques, and environmental concerns surrounding CBM development in the PRB.

Origins
Coal bed methane, or coal bed natural gas (CBM or CBNG), results from the coalification process; increased temperatures due to increased burial depth drives volatiles, such as methane, from humic material via biogenic and thermogenic processes. Thermogenic processes yield much greater volumes of methane per ton of coal than biogenic processes (Figure 42). Wyoming coals are humic coals containing type III vitrinitic kerogen derived from woody terrestrial plants. The presence of type III vitrinitic kerogen classifies these as dry-gas generating – methane and little to no complex alkanes (ethane, propane, butane, pentane).

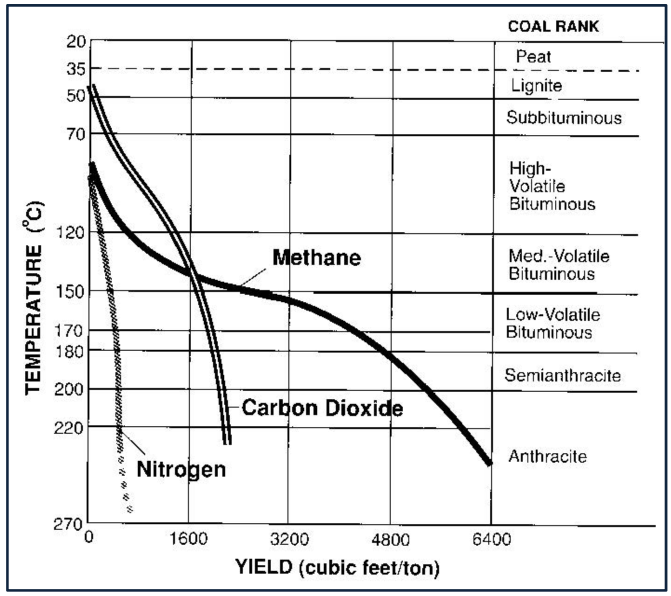


Figure 42: Thermogenic methane generation during coalification Rightmire, 1984)

Biogenic methane is generated in peat only after aerobic bacteria have metabolized all free oxygen and /or anaerobic bacteria have metabolized all sulfates. Then, other species of anaerobic bacteria reduce carbon dioxide and produce methane. After the coal has been subjected to 50^{o} C for a geologically significant period of time, almost all biogenic methane will have been produced and only one-third of the original moisture is left in the coal. The coal then begins to exhibit a vitreous luster and reaches the rank of sub-bituminous coal. Nearly all Powder River Basin (PRB) coal is sub-bituminous and in some cases lignite (a lower, less mature coal rank).

Above 50^{o} C, thermogenic processes begin. These liberate more water from the coal, in addition to nitrogen, carbon dioxide, and minor methane, as the coal transitions to the rank of high volatile bituminous coal. When burial temperatures reach 150^{o} C, maximum thermogenic methane occurs and the coal transitions to the rank of low volatile bituminous coal. Methane continues to be generated with increasing temperature and coal rank.

Powder River Basin coals of the Wasatch and Fort Union formations are thermally immature and thus within the less productive biogenic methane window. Despite this fact, several individual coal beds in the Powder River Basin are over 100 feet thick, and locally over 200 feet thick, resulting in a large aggregate thickness of coal. This in turn compensates for the lower yield per ton associated with biogenic processes, and results in large methane reserves for the Powder River Basin.

CBM Production History and Techniques

Commercial CBM production in the PRB began in 1986 when Wyatt Petroleum completed a well in the Fort Union Formation near Recluse, Wyoming, north of Gillette that produced 24 thousand cubic feet (MCF) of methane per day. Wyatt Petroleum and other operators consequently completed a number of wells in Tongue River Member of the Fort Union Formation also in the Recluse, WY area with daily production ranging from 3 to 453 MCF of methane. In 1989, Rawhide Butte, north of Gillette, was the site of the first effort to commercially extract CBM directly from the coal beds. Gas was discovered when residents in a subdivision reported gas in their basements and under their streets. The subdivision was eventually abandoned.

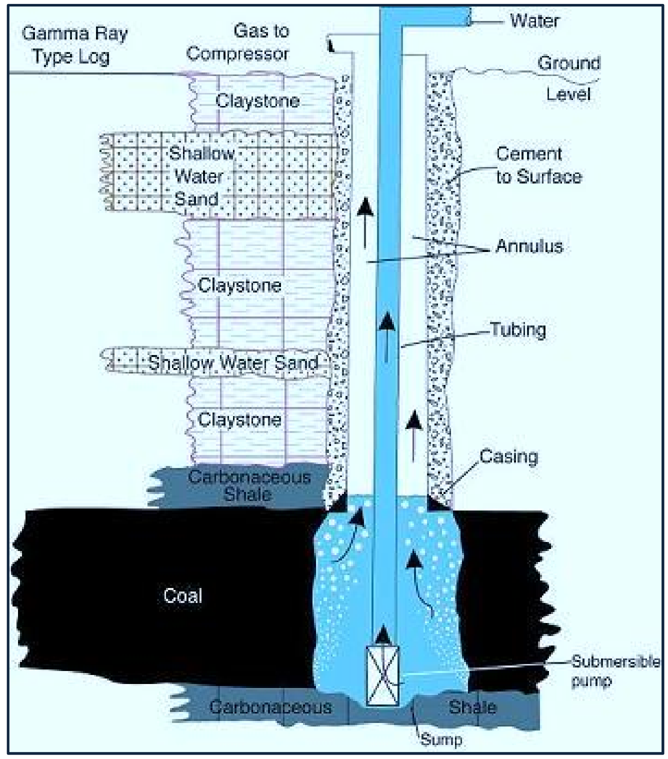


Figure 43: Coal bed methane well completion technology (De Bruin and Lyman, 1999)

Acceleration of CBM activity took place in the late 1990s, due primarily to development of an open-hole well completion technique which enhanced production and lowered costs. The technique involves drilling to the top of the target coal bed and setting casing. The coal bed is then underreamed and cleaned out with fresh water. Coal bed water is then produced from a submersible pump attached to tubing while the gas is produced from the well's annulus (Figure 43). Large volumes of water are produced when recovering CBM; with an average of over 400 barrels of water per day during the de-watering stage of a Powder River Basin CBM well. This de-watering stage, intended to de-pressurize the reservoir allowing methane to exsolve from formation water, may last as long as two years before onset of the stable production stage (Figure 44). Most of the water is fresh and discharged to the surface creating new wetland habitat areas or is used for agricultural irrigation.

By 1997, CBM monthly production in the PRB had reached 1 billion cubic feet (BCF) from roughly 200 producing wells. In late 1999, monthly production had reached over 5 BCF from over 1,000 producing wells with about 800 wells shut-in and awaiting the completion of pipeline infrastructure. Yearly production has increased to the current production of about 0.5 TCF (trillion cubic feet) per year with over 7000 wells producing. Coal bed methane and water production for the Powder River Basin from 1997 to 2010 is summarized in Figures 45 and 46.

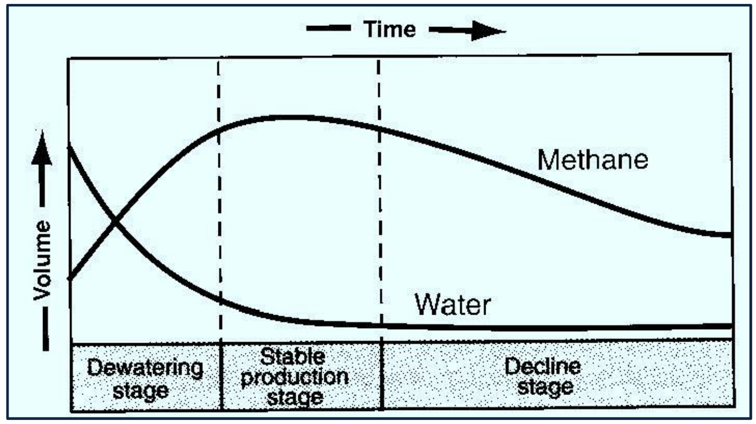


Figure 44: Production history of a CBM well (De Bruin and Lyman, 1999).

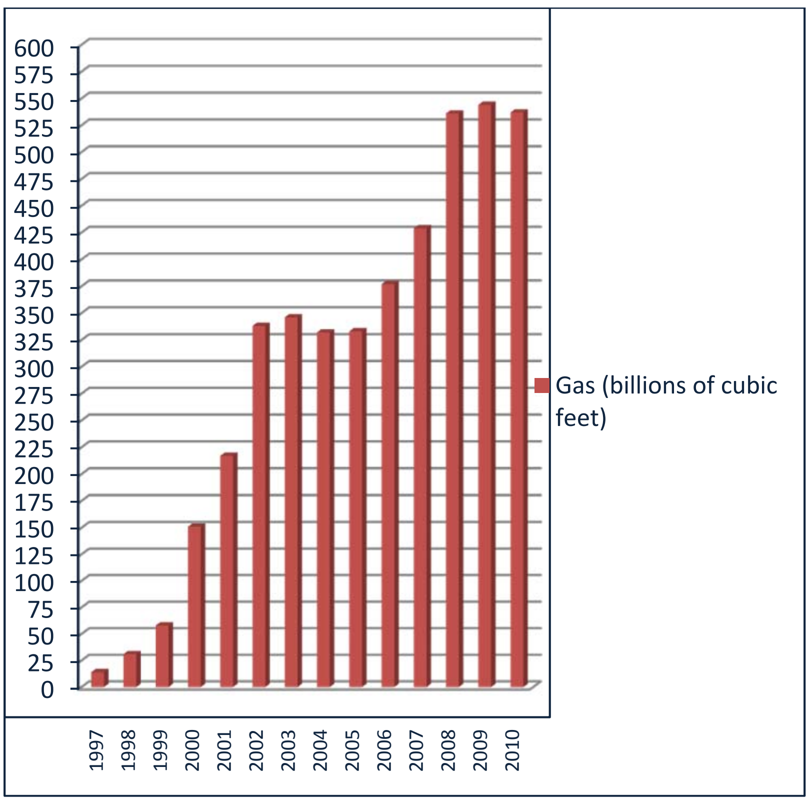


Figure 45: Powder River Basin methane production from 1997 – 2010 (Wyoming Oil and Gas Conservation Commission, 2011)

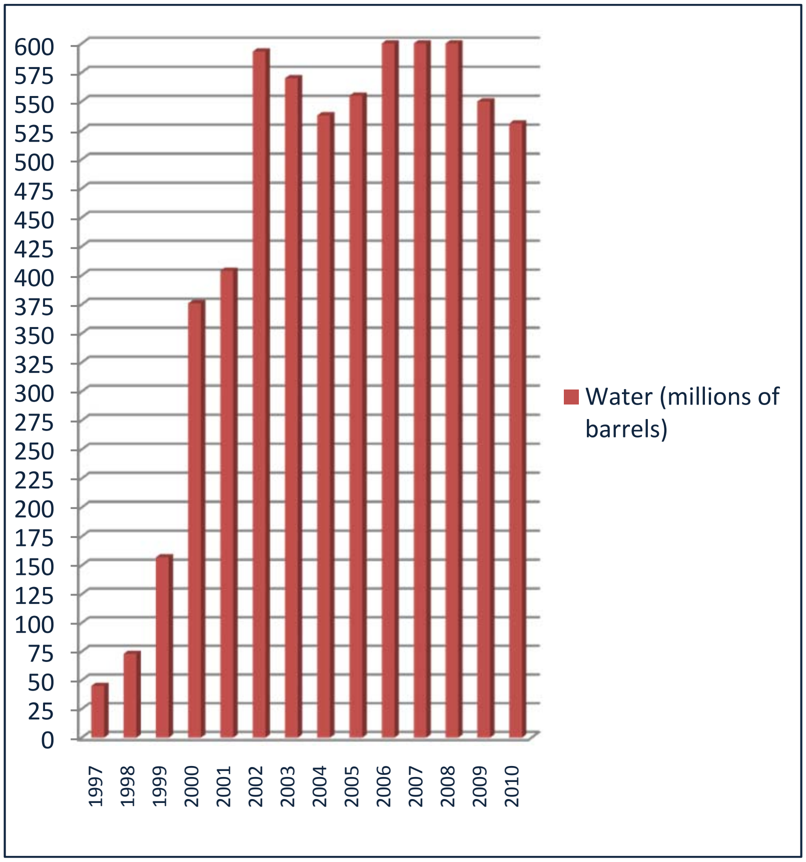


Figure 46: Powder River Basin coal bed methane water production from 1997 – 2010 (Wyoming Oil and Gas Conservation Commission, 2011)

Reserves

As there are several methods used to estimate the amount of recoverable gas from a coal bed and as such reserve estimates vary. Recoverable CBM reserves of the Powder River Basin have been estimated by the U. S. Geological Survey (2001) at 8.24 - 22.42 trillion cubic feet (TCF). The Wyoming Oil and Gas Conservation Commission (2002) estimated 31.8 TCF of recoverable CBM in the Powder River Basin of Wyoming alone. The Montana Bureau of Mines and Geology and the U.S. Department of Energy have separately estimated 0.8 - 1.0 TCF of recoverable CBM in the Montana portion of Powder River Basin.

Coal Bed Methane Water and the Environment

The primary environmental concern regarding CBM development is related to the surface disposal of the large quantities of produced water. In the Powder River Basin, produced CBM water becomes increasingly saline and sodium-rich moving north and west through the basin. In these high salinity and sodium zones, irrigation with CBM water must be managed closely.

Over time, salts can accumulate in the root zone and adversely affect plant growth. Also, sodic irrigation water can impair soil hydraulic conductivity through creation of soil crusts. When soils contain swelling clays are wetted, sodium results in an increase in the degree of swelling, in turn leading to dispersion and migration of clay particles. The risk of sodium degradation has been observed in other soil textures. Crusting, poor soil tilth, hard setting and aggregate failure on a sandy loam soil irrigated with water with EC ~ 1 and SAR ~ 7 have been observed. Minhas (1994) saw irreversible and severe reduction in infiltration on sandy loam soil with long term irrigation under high SAR water followed by monsoon rain.

Day 5 Energy Industry Site Visit - Dry Fork Station and Coal Mine

Dry Fork Station, located about seven miles north of Gillette, WY, is a coal-based electric generation power plant owned by Basin Electric Power Cooperative and the Wyoming Municipal Power Agency. Not yet operational, the power plant is under construction and about 99.6% complete.

A one mile-long conveyor system from the adjacent Dry Fork Mine will fuel Dry Fork Station with sub-bituminous coal from the Tongue River Member of the Fort Union Formation.

The maximum power output is estimated at 385 MW, while the rated capacity of the station is 422 MW. This is sufficient to provide electricity for 308,000 homes.

During 2009, the Dry Fork Station experienced a peak construction work force of more than 1,300 construction workers. After completion of construction, 83 positions will be required to operate the plant. Construction costs are estimated at roughly one billion dollars.

Gillette to Buffalo Roadside Geology

For the seventy miles from Gillette to Buffalo, I-90 traverses rolling sagebrush-covered grasslands of the central Powder River Basin and over the poorly exposed, nearly flat lying, Eocene Wasatch Formation.

The unusually small ‘tepee’ buttes west of Gillette are underlain by resistant caps of red-orange clinker.

Thirty-two miles from Gillette the interstate crosses the Powder River. Good outcrops of Wasatch formation sandstone and claystone with abundant petrified wood remains appear in the bluffs along the western side of the Powder River valley.

Good clinker outcrops as the I-90 descends into the Clear Creek valley and Buffalo. Continue along I-90 to Sheridan.

Bibliography

Aho, G., 2011, Overview of Enefit American Oil's Plan of Operation, verbal communication, July 26, 2011.

Armstrong, F.C., 1970, Geologic factors controlling uranium resources in the Gas Hills District, Wyoming, 22nd Annual Field Conference, Wyoming Geological Association Guidebook, p. 31-44.

Ayers, W.B., and Kaiser, W.R., 1984, Lacustrine-interdeltaic coal in the Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana, U.S.A., in Rahmani, R.A. and Flores, R.M., eds., Sedimentology of Coal and Coal-bearing Sequences: International Association of Sedimentologists Special Publication No. 7, p. 61-84.

Baker, D.R., 1962, The Newcastle Formation in Weston County, Wyoming: A nonmarine (alluvial) plain deposit, 17th Annual Field Conference Guidebook, Wyoming Geological Association, p. 148-162.

Boyd, H.A., 1994, The "Great Lignite", "Ceratops Beds" and associated lithostratigraphic units at the K/T boundary, Powder River Basin, Wyoming, 44th Annual Field Conference, Wyoming Geological Association Guidebook, p. 61-76.

Brown, R.W., 1958, Fort Union Formation in the Powder River Basin, Wyoming: Wyoming Geological Association Guidebook, 13th Annual Field Conference, p. 111-113.

Bureau of Land Management, 2010, Cameco Gas Hills Uranium Project Plan of Operations.pdf, retrieved from http://www.blm.gov/pgdata/etc/medialib/blm/wy/information/NEPA/lfodocs/gashills/scoping.Par.23286.File.dat/Map_GrazingAllotments_24x36.pdf on July 23, 2011.

Bureau of Land Management, 2006, Environmental Assessment, Chevron Oil Shale Research, Development & Demonstration, CO-110-2006-120-EA, retrieved from http://www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/white_river_field/oil_shale/chevron_u_s_a__inc.Par.26834.File.dat/CO1102006120EAwofigures.pdf on July 6, 2011, 150 p.

Cameco Resources, 2011, Uranium Operations Fact Sheet 2011.pdf, retrieved from http://www.cameco.com/mining/ on July, 12, 2011.

Cameco Resources, 2011, In-situ Uranium Recovery.jpg, retrieved form http://www.cameco.com/mining/experience/ on July 11, 2011.

Coates, D.A. and Heffern, E.L., 1999, Origin and Geomorphology of Clinker in the Powder River Basin, Wyoming and Montana, in Miller, W.R., ed., Coalbed Methane and Tertiary Geology of the Powder River Basin Wyoming and Montana, Fiftieth Field Conference Guidebook, Wyoming Geological Association, p. 211-229.

Darton, N.H., 1909, Geology and Water Resources of the Northern Portion of the Black Hills and Adjoining Regions in South Dakota and Wyoming, United State Geological Survey Professional Paper No. 65.

De Bruin, R.H. and Lyman, R.M., 1999, Coalbed Methane in Wyoming, in Miller, W.R., ed., Coalbed Methane and Tertiary Geology of the Powder River Basin Wyoming and Montana, Fiftieth Field Conference Guidebook, Wyoming Geological Association, p. 61-72.

Ellis, M.S., Gunther, G., Flores, R.M., Ochs, A.M., Stricker, G.D., Roberts, S.B., Taber, T.T., Bader, L.R., and Schuenemeyer, J.H., 1999, Preliminary report on coal resources of the Wyodak-Anderson coal zone, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 98-789A, 49 p.

Flores, R.M., 1999, Stratigraphic Correlation of the Wyodak-Anderson Coal Zone in the Powder River Basin, Montana and Wyoming: a tale of uncorrelatable coal beds, in Miller, W.R., ed., Coalbed Methane and Tertiary Geology of the Powder River Basin Wyoming and Montana, Fiftieth Field Conference Guidebook, Wyoming Geological Association, p. 1-24.

Flores, RM., Stricker, G.D., Meyer, J., Doll, T.E., Norton, P.H., Livingston, R.J., and Jennings, M.C., 2001, A field conference on impacts of coalbed methane development in the Powder River Basin, Wyoming. USGS Open File Report 01-126, 26 p.

Hanley J.H., 1976, Paleosynecology of nonmarine Mollusca from the Green River and Wasatch formations (Eocene), southwestern Wyoming and northwestern Colorado, In: Scott R.W. and WestR.R. (eds.), Structure and Classification of Paleocommunities.Dowden, Hutchinson & Ross, Stroudsburg, p. 235–261.

Halvorsen, D.L., 1980, Geology and petrology of Devils Tower, Missouri Buttes, and Barlow Canyon area, Crook County, Wyoming [Ph.D. thesis]: Grand Forks, University of North Dakota, 218 p.

Hausel, W.D., and Hull, J., 1990, Guide to gold mineralization and Archean geology of the South Pass greenstone belt, Wind River Range, Wyoming, in Roberts, S., *Geologic Field Trips to Western Wyoming:* Geological Survey of Wyoming Public Information 29, p. 178-191.

Hausel, W.D., 1990, Geologic map of the South Pass granite-greenstone belt, southern Wind River Range, western Wyoming: Geological Survey of Wyoming, Report of Investigations 44-plate 1, scale 1:48,000.

Heffern, E.L. and Coates, D.A., 2004, Geologic history of natural coal-bed fires, Powder River basin, USA, in Coal Fires Burning around the World: a Global Catastrophe, International Journal of Coal Geology, Volume 59, p. 25-47.

Johnson, R.C., Mercier, T.J., and Brownfield, M.E., 2011, Assessment of in-place oil shale resources of the Green River Formation, Greater Green River Basin in Wyoming, Colorado, and Utah: U.S. Geological Survey Fact Sheet 2011–3063, 4 p.

Karner,F., 1981, Geologic relationships in the western centers of the northern Black Hills Cenozoic igneous province, in Rich, F.J., ed., Geology of the Black Hills, South Dakota and Wyoming: Field Trip Guidebook for G.S.A. Rocky Mountain Section Meeting, American Geological Institute, p.126-133.

Karner,F.R. and Halvorson, D.L., 1987, The Devils Tower, Bear Lodge Mountains, Cenozoic igneous complex, Northeastern Wyoming, in Beus, S.S., ed., Rocky Mountain Section of the G.S.A,. Centennial Field Guide Volume 2, Rocky Mountain section, p. 161-164.

King, J.W. and Austin, S.R., 1966, Some characteristics of roll-type uranium deposits at Gas Hills, Wyoming, Mining Engineering, Society of Mining Engineers, p. 73-80.

Lageson, D.R. and Spearing, D.R, 1991, Roadside Geology of Wyoming, 2nd revised edition, Mountain Press Publishng Company, Missoula, Montana, 271 p.

Mapel, W.J., and Pillmore, C.L., 1963, Geology of the Inyan Kara Mountain Quadrangle, Crook and Weston Counties, Wyoming: U.S. Geological Survey Bulletin 1121-M, 56 p.

Minhas, P.S., Naresh, R.K., Chauhan, C.P.S., Gupta, R.K., 1994, Field determined hydraulic properties of a sandy loam soil irrigated with various salinity and SAR waters, Agricultural Water Management, Volume 25, Issue 2, p. 97-108.

New Era Petroleum, 2011, The New Era Technology, retrieved from http://www.new-era-petroleum.com/technology.php on July 21, 2011

Nichols, D.J., Wolfe, J.A., and Pocknall, D.T., 1989, Latest Cretaceous and early Tertiary history of vegetation in the Powder River Basin, Montana and Wyoming: 28th International Geological Congress, Field Trip Guidebook T 132, p. 28-33.

Nielsen, G.B., 2010, Regional correlation of diagenetic coloration facies and analysis of iron oxide cementation processes, Jurassic Navajo Sandstone, southwestern Utah [PhD thesis]: University of Utah, 269 p.

Pietras, J.T., Carroll, A.R. and Rhodes, M.K., 2003, Lake basin response to tectonic drainage diversion: Eocene Green River Formation, Wyoming, Journal of Paleolimnology, v. 30, p. 115–125.

Rare Element Resources, 2010, Bear Lodge Rare Earth Project Summary, retrieved from http://www.rareelementresources.com/i/pdf/BearLodge-Summary.pdf on July 16, 2011

Red Leaf Resources, 2011, EcoShale In-Capsule Technology, retreived from http://www.redleafinc.com/index.php?option=com_content&view=article&id=26:technology&catid=3:technology&Itemid=4) on July 14, 2011.

Rightmire, C.T., 1984, Coalbed methane resources, in Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists Studies in Geology Series No. 17, p. 1-13.

Roehler H.W., 1992, Description and correlation of Eocene rocks in stratigraphic reference sections for the Green River and Washakie basins, southwest Wyoming. United States Geological Survey Professional Paper 1506D, 83 p.

Roehler H.W., 1993, Eocene climates, depositional environments, and geography, Greater Green River Basin, Wyoming, Utah, and Colorado. United States Geological Survey Professional Paper 1506F, 74 p.

Ryder, R.T., Lee, M.W., and Smith, G.N., 1981, Case Histories: Rozet Field, Cambell County, Wyoming, in Volume Methods in Exploration Series #2: Seismic Models of Sandstone Stratigraphic Traps in Rocky Mountain Basins, American Association of Petroleum Geologists, p. 56 – 59.

Shell Frontier Oil and Gas Inc., 2006, Plan of Operations, Oil Shale Test Project, Oil Shale Research and Development Project, retrieved from http://www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/white_river_field/oil_shale.Par.79837.File.dat/OSTPlanofOperations.pdf on July 15, 2011.

Snow, C.D., 2011, Technical Report on the Gas Hills Uranium Project, Fremont and Natrona Counties, Wyoming, 136 p.

Staatz, M.H., 1983: Geology and Description of Thorium and Rare-Earth Deposits in the Southern Bear Lodge Mountains, Northeastern Wyoming; U.S. Geological Survey Professional Paper 1049-D.

Stone, D.S., 2003, New interpretations of the Piney Creek thrust and associated Granite Ridge tear fault, northeastern Bighorn Mountains, Wyoming, Rocky Mountain Geology, v. 38, no. 2, p. 205-235.

Strathmore Minerals Corporation, 2011, May 2011 Corporate Update, retrieved from http://www.strathmoreminerals.com/i/pdf/Corporate-Update-PPT-May-2011.pdf on July 16, 2011

Stuckless, J.S., Hedge, C.E., Worl, R.G., Simmons, K.R., Nkomo, I.T., and Wenner, 1985, Isotopic studies of the late Archean plutonic rocks of the Wind River Range, Wyoming: Geological Society of America Bulletin, v.96, p. 850-860.

Symington, W.A., Olgaard, D.L., Otten, G.A., Phillips, T.C., Thomas, M.M., and Yeakel, J.D., 2008, ExxonMobil's Electrofrac Process for In Situ Oil Shale Conversion, in Proceedings, American Association of Petroleum Geologists Annual Convention and Exhibit, San Antonio, TX.

United States Energy Information Administration, 2010, Year-end 2008 estimates of U.S. uranium reserves, retrieved from http://www.eia.gov/cneaf/nuclear/page/reserves/ures.html on July 27, 2011.

Wasilk, N.J. and Robinson, E.T., 1980, The Commercial Scale Refining of Paraho Crude Shale Oil Into Military Specification Fuels, in Proceedings, Symposium on Oil Shale and Tar Sands, Division of Fuel Chemistry, American Chemical Society, Los Angeles, CA, p. 12.

World Nuclear Association, 2010, Known Recoverable Resources of Uranium 2009, retrieved from http://www.world-nuclear.org/info/inf75.html on July 28, 2011.

Wyodak Resources, 2005, retrieved from http://www.wyodak.com/ on July 8, 2011.
Wyoming Oil and Gas Conservation Commission, 2011, data retrieved from http://wogcc.state.wy.us on July 17, 2011.