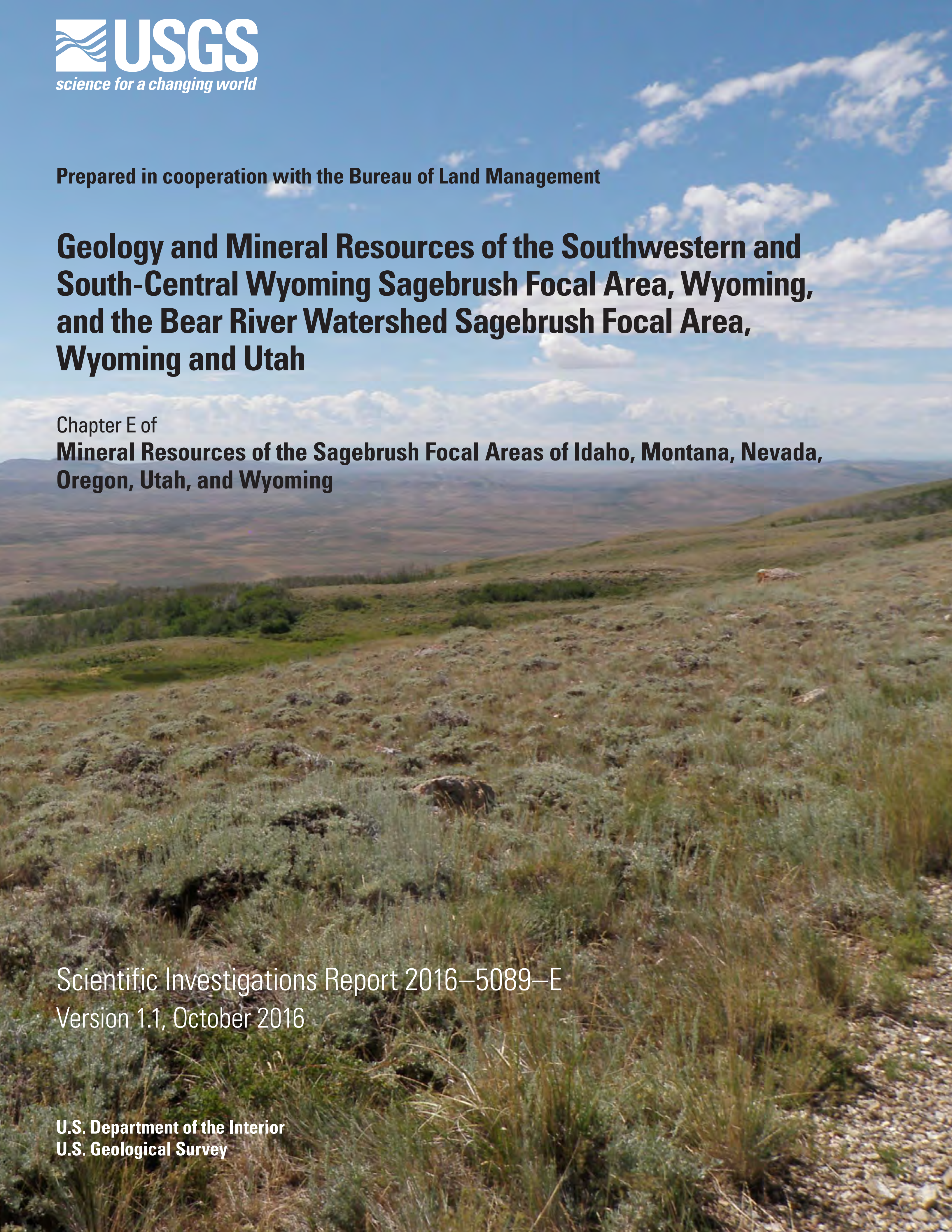

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# Geology and Mineral Resources of the Southwestern and South-Central Wyoming Sagebrush Focal Area, Wyoming, and the Bear River Watershed Sagebrush Focal Area, Wyoming and Utah

Chapter E of
**Mineral Resources of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming**

Scientific Investigations Report 2016–5089–E
Version 1.1, October 2016

**U.S. Department of the Interior**
**U.S. Geological Survey**

**COVER.** View looking southeast from the east flank of South Mountain, Wyoming (between the Fossil Basin and Fontenelle blocks). Topography and vegetation is typical of much of the study area. Phosphate was mined from the Phosphoria Formation at South Mountain for a few years after World War II. The target bed was less than 1.4 m thick and contained 21 percent $P_2O_5$. Photograph by Anna Wilson, U.S. Geological Survey, 2010.

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By Anna B. Wilson, Timothy S. Hayes, Mary Ellen Benson, Douglas B. Yager, Eric D. Anderson, Donald I. Bleiwas, Jacob DeAngelo, Connie L. Dicken, Ronald M. Drake II, Gregory L. Fernette, Stuart A. Giles, Jonathan M.G. Glen, Jon E. Haacke, John D. Horton, Heather L. Parks, Barnaby W. Rockwell, and Colin F. Williams

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**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
SALLY JEWELL, Secretary

**U.S. Geological Survey**
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia
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# Contents

# Figures

## Tables

# Conversion Factors

[U.S. customary units to International System of Units]

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.4047 | square hectometer ($hm^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square foot ($ft^2$) | 929.0 | square centimeter ($cm^2$) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square inch ($in^2$) | 6.452 | square centimeter ($cm^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| barrel (bbl; petroleum, 1 barrel=42 gal) | 0.1590 | cubic meter ($m^3$) |
| | Mass | |
| ounce, troy (oz) | 31.103 | gram (g) |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| ton, short (2,000 lb) | 0.9072 | metric ton (t) |
| ton, long (2,240 lb) | 1.016 | metric ton (t) |

[International System of Units to U.S. customary units]

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| kilometer (km) | 0.5400 | mile, nautical (nmi) |
| meter (m) | 1.094 | yard (yd) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| square kilometer ($km^2$) | 247.1 | acre |
| square centimeter ($cm^2$) | 0.001076 | square foot ($ft^2$) |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |
| square centimeter ($cm^2$) | 0.1550 | square inch ($ft^2$) |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |
| | Volume | |
| cubic meter ($m^3$) | 6.290 | barrel (petroleum, 1 barrel = 42 gal) |
| cubic meter ($m^3$) | 264.2 | gallon (gal) |
| cubic meter ($m^3$) | 0.0002642 | million gallons (Mgal) |
| cubic centimeter ($cm^3$) | 0.06102 | cubic inch ($in^3$) |

| Multiply | By | To obtain |
|---|---|---|
| cubic meter ($m^3$) | 35.31 | cubic foot ($ft^3$) |
| cubic meter ($m^3$) | 1.308 | cubic yard ($yd^3$) |
| cubic kilometer ($km^3$) | 0.2399 | cubic mile ($mi^3$) |
| cubic meter ($m^3$) | 0.0008107 | acre-foot (acre-ft) |
| | Mass | |
| gram (g) | 0.032 | ounce, troy (oz) |
| gram (g) | 0.03527 | ounce, avoirdupois (oz) |
| kilogram (kg) | 2.205 | pound avoirdupois (lb) |
| metric ton (t) | 1.102 | ton, short [2,000 lb] |
| metric ton (t) | 0.9842 | ton, long [2,240 lb] |
| | Density | |
| kilogram per cubic meter ($kg/m^3$) | 0.06242 | pound per cubic foot ($lb/ft^3$) |
| gram per cubic centimeter ($g/cm^3$) | 62.4220 | pound per cubic foot ($lb/ft^3$) |

# Supplemental Information

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

# Datum

Vertical coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

## Abbreviations

| | |
|---|---|
| Ad | andradite (iron-rich garnet) |
| AMIS | Automated Minerals Information System |
| AOC | Assessment Oversight Committee |
| API | American Petroleum Institute |
| AR | “as received” |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| ASTM | American Society for Testing and Materials |
| AU | assessment unit (oil and gas) |
| BCF, BCFG | billion cubic feet (of gas) |
| BHT | bottom-hole temperature |
| BLM | Bureau of Land Management |
| BRW | Bear River Watershed (Sagebrush Focal Area) |
| BV | “best value” |
| CAGR | compound annual growth rate |
| CAI | conodont alteration index |
| CFR | Code of Federal Regulations |
| CIGS | copper-indium-gallium selenide |
| CSA | Canadian Standards Association |
| CSM | clay-sulfate-mica |
| CSAMT | controlled-source audiofrequency magnetotellurics |
| DLA | Defense Logistics Agency |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| EGS | enhanced geothermal system |
| EIS | Environmental Impact Statement |
| ETM+ | Landsat 7 Enhanced Thematic Mapper Plus |
| FLPMA | Federal Land Policy and Management Act of 1976 |
| f.o.b. | free on board |
| FWS | U.S. Fish and Wildlife Service |
| g/t | gram per metric ton |
| Ga | giga-annum or billions of years ago |
| GFTZ | Great Falls Tectonic Zone |
| GHC | Geo-Heat Center |

| | |
|---|---|
| GIS | geographic information system |
| HSSR | Hydrogeochemical and Stream Sediment Reconnaissance |
| IDW | inverse distance weighted |
| LEDs | light-emitting diodes |
| LLD | lower limit(s) of determination |
| m.y. | millions of years |
| Ma | mega-annum or millions of years ago |
| MAS | Minerals Availability System |
| MCF | thousand cubic feet of gas |
| MILS | Mineral Industry Location System |
| MMBO | million barrels of oil |
| MMBNGL | million barrels of natural gas liquids |
| MOP | muriate of potash |
| Moz | million troy ounces |
| MRDS | Mineral Resources Data System |
| Mt | million metric tons |
| MTU | metric ton unit |
| MVT | Mississippi-Valley-type |
| MW | megawatt |
| MWe | megawatt electricity |
| NASGLP | North American Soils Geochemical Landscape Project |
| NBMG | Nevada Bureau of Mines and Geology |
| NDS | National Defense Stockpile |
| NEPA | National Environmental Policy Act of 1989 |
| NGDB | National Geochemical Database |
| NGL | natural gas liquids |
| NGS | National Geochemical Survey |
| NMIC | USGS National Minerals Information Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NOGA | USGS National Oil and Gas Assessment |
| NURE | National Uranium Resource Evaluation |
| NWR | National Wildlife Refuge |
| opt | troy ounce per short ton |
| oz | troy ounce |
| PGE | platinum-group element |

| | |
|---|---|
| PGM | platinum-group metal |
| PLSS | Public Land Survey System |
| ppm | parts per million |
| REE | rare earth element |
| REOE | rare earth oxide equivalent(s) |
| RMOTC | Rocky Mountain Oilfield Testing Center |
| ROD | Record of Decision |
| RTP | reduction-to-the-pole or reduced-to-pole |
| SaMiRA | Sagebrush Mineral-Resource Assessment |
| SEDAR | Canadian System for Electronic Document Analysis and Retrieval |
| SEDEX | sedimentary exhalative |
| SFA | Sagebrush Focal Area |
| SG | specific gravity |
| SI | structural index |
| SOP | sulfate of potash |
| SWIR | shortwave-infrared (region of the electromagnetic spectrum) |
| t | metric ton |
| TCM | Tax Court Memorandum |
| Th/K | thorium/potassium ratio |
| TMI | total magnetic intensity |
| TOMS | Topographically Occurring Mine Symbols |
| TPS | total petroleum system |
| UMOS | Utah Mineral Occurrence System |
| USBM | former U.S. Bureau of Mines |
| USFS | U.S. Forest Service |
| USGS | U.S. Geological Survey |
| USMIN | USGS Mineral Deposit Database |
| VMS | volcanogenic massive sulfide |
| wt.% | weight percent |
| WYO | Southwestern and South-Central Wyoming (Sagebrush Focal Area) |

# Chemical Symbols and Formulas Used

| | | | |
|---|---|---|---|
| Ag | silver | Gd | gadolinium |
| Al | aluminum | Ge | germanium |
| $Al_2O_3$ | aluminum oxide | H | hydrogen |
| Ar | argon | $H_2S$ | hydrogen sulfide |
| As | arsenic | Hf | hafnium |
| Au | gold | Hg | mercury |
| B | boron | Ho | holmium |
| Ba | barium | In | indium |
| $BaSO_4$ | barium sulfate | Ir | iridium |
| Be | beryllium | K | potassium |
| Bi | bismuth | $K_2O$ | potassium oxide |
| Br | bromine | La | lanthanum |
| C | carbon | Li | lithium |
| $C_{org}$ | organic carbon | Lu | lutetium |
| CO | carbon monoxide | Mg | magnesium |
| $CO_2$ | carbon dioxide | MgO | magnesium oxide |
| Ca | calcium | Mn | manganese |
| CaO | calcium oxide | Mo | molybdenum |
| Cd | cadmium | N | nitrogen |
| Ce | cerium | $NH_3$ | ammonia |
| $CH_4$ | methane | Na | sodium |
| Cl | chlorine | NaCl | sodium chloride |
| Co | cobalt | $Na_2O$ | sodium oxide |
| Cr | chromium | Nb | niobium |
| Cs | cesium | Nd | neodymium |
| Cu | copper | Ni | nickel |
| Dy | dysprosium | O | oxygen |
| Er | erbium | Os | osmium |
| Eu | europium | P | phosphorous |
| F | fluorine | $P_4$ | elemental (white) phosphorus |
| Fe | iron | $PO_4$ | phosphate |
| $Fe_2O_3$ | ferric iron oxide | $P_2O_5$ | phosphorous pentoxide |
| Ga | gallium | Pb | lead |
| GaAs | gallium arsenide | Pd | palladium |
| GaN | gallium nitride | Pr | praseodymium |

| | | | |
|---|---|---|---|
| Pt | platinum | Te | tellurium |
| Rb | rubidium | Th | thorium |
| Re | rhenium | Ti | titanium |
| Rh | rhodium | $TiO_2$ | titanium dioxide |
| Ru | ruthenium | Tm | thulium |
| S | sulfur | Tl | thallium |
| Sb | antimony | U | uranium |
| Sc | scandium | $U_3O_8$ | triuranium octaoxide (yellowcake) |
| Se | selenium | V | vanadium |
| Si | silicon | $V_2O_5$ | vanadium pentoxide |
| $SiO_2$ | silicon dioxide (silica) | W | tungsten |
| Sm | samarium | $WO_3$ | tungsten trioxide |
| Sn | tin | Y | yttrium |
| Sr | strontium | Yb | ytterbium |
| Ta | tantalum | Zn | zinc |
| Tb | terbium | Zr | zirconium |

# Mineral Formulas Used

| | |
|---|---|
| adularia | $KAlSi_3O_8$ |
| alunite | $KAl_3(SO_4)_2(OH)_6$ |
| andradite (garnet) | $Ca_3Fe^{3+}{}_2(SiO_4)_3$ |
| ankerite | $Ca(Fe,Mg,Mn)(CO_3)_2$ |
| argentite | $Ag_2S$ |
| arsenopyrite | FeAsS |
| barite | $BaSO_4$ |
| bornite | $Cu_5FeS_4$ |
| cassiterite | $SnO_2$ |
| chalcocite | $Cu_2S$ |
| chalcopyrite | $CuFeS_2$ |
| cinnabar | HgS |
| clinoptilolite (zeolite) | $(Ca,Na,K)_{2\text{-}3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12(H_2O)$ |
| coffinite | $U[SiO_4,(OH)_4]$ |
| corderoite | $Hg_3S_2Cl_2$ |
| dolomite | $CaMg(CO_3)_2$ |
| erionite (zeolite) | $(Ca,Na,K)_{10}[Al_{10}Si_{26}O_{72}]\cdot\sim 30H_2O$ |
| fluorite | $CaF_2$ |
| galena | PbS |
| hectorite (smectite clay) | $Na_3(Mg,Li)_3Si_4O_{10}(F,OH)_2$ |

| | |
|---|---|
| hematite | $Fe_2O_3$ |
| ilmenite | $FeTiO_3$ |
| kaolinite | $Al_2Si_2O_5(OH)_4$ |
| leucite | $K(AlSi_2O_6)$ |
| magnetite | $Fe_3O_4$ |
| molybdenite | $MoS_2$ |
| molybdite | $MoO_3$ |
| monazite | $(Ce,La,Th,Nd)PO_4$ |
| montmorillonite | $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$ |
| nepheline | $Na_3KAl_4Si_4O_{16}$ |
| opal | $SiO_2 \cdot nH_2O$ |
| phillipsite (zeolite) | $(Ca,Na,K)_{4-7}[Al_{4-7}Si_{2-9}O_{32}] \cdot 12H_2O$ |
| powellite | $CaMoO_4$ |
| pyrite | $FeS_2$ |
| quartz | $SiO_2$ |
| rutile | $TiO_2$ |
| scheelite | $CaWO_4$ |
| siderite | $FeCO_3$ |
| sillimanite | $Al_2SiO_5$ |
| sylvite | KCl |
| sylvinite | KCl+NaCl |
| sphalerite | (Zn,Fe)S |
| staurolite | $Fe_2Al_9Si_4O_{23}(OH)$ |
| stilpnomelane | $(K,Ca,Na)(Fe^{2+},Mg,Fe^{3+})_8(Si,Al)_{12}(O,OH)_{27} \cdot nH_2O$ |
| tetrahedrite | $(Cu,Fe,Ag,Zn)_{12}Sb_4S_{13}$ |
| uraninite | $UO_2$ |
| xenotime | $YPO_4$ |
| zircon | $ZrSiO_4$ |

# Geology and Mineral Resources of the Southwestern and South-Central Wyoming Sagebrush Focal Area, Wyoming, and the Bear River Watershed Sagebrush Focal Area, Wyoming and Utah

By Anna B. Wilson, Timothy S. Hayes, Mary Ellen Benson, Douglas B. Yager, Eric D. Anderson, Donald I. Bleiwas, Jacob DeAngelo, Connie L. Dicken, Ronald M. Drake, II, Gregory L. Fernette, Stuart A. Giles, Jonathan M.G. Glen, Jon E. Haacke, John D. Horton, Heather L. Parks, Barnaby W. Rockwell, and Colin F. Williams

## Executive Summary

The U.S. Department of the Interior has proposed to withdraw approximately 10 million acres of Federal lands from mineral entry (subject to valid existing rights) from 12 million acres of lands defined as Sagebrush Focal Areas (SFAs) in Idaho, Montana, Nevada, Oregon, Utah, and Wyoming (for further discussion on the lands involved see Day and others, 2016).The purpose of the proposed action is to protect the greater sage-grouse (*Centrocercus urophasianus*) and its habitat from potential adverse affects of locatable mineral exploration and mining. To inform the decision on whether to withdraw the SFAs from mineral entry, the Bureau of Land Management requires a mineral-resource assessment be completed to identify mineral resources within the proposed withdrawal area. The USGS Sagebrush Mineral-Resource Assessment (SaMiRA) project was initiated in November 2015 and supported by the BLM to (1) assess locatable mineral-resource potential and (2) to describe leasable and salable mineral resources for the seven SFAs and Nevada additions.

This report provides information about mineral resources and their potential to occur within study areas that include proposed withdrawal areas within the central part of the Southwestern and South-Central Wyoming and Bear River Watershed, Wyoming and Utah, SFAs. Together, the Public Land Survey System (PLSS) townships that contain these parcels are referred to as the Wyoming-Utah study area (figs. 1 and 2). The methodology used for the assessment for locatable mineral resource potential and levels of certainty are reviewed in Day and others (2016) and classification criteria are described in appendix 1.

Most of the study area is in the greater Green River Basin, a paleobasin whose modern topographic expression is an intermontane desert covering 51,800 square kilometers ($km^2$) (20,000 square miles, $mi^2$) in southwest Wyoming, northeast Utah, and northwest Colorado (Roehler, 1992). The structural framework of the greater Green River Basin was established during the Laramide orogeny (70–35 million years ago or mega-annum, Ma), beginning in the Late Cretaceous. Three intrabasin anticlines subdivide the basin into four structural and topographic subbasins (Roehler, 1992).

Eocene sedimentary deposits of lacustrine and fluvial origin dominate the greater Green River Basin area, where they are as much as 3,050 m (about 10,000 feet, ft) thick. Important rock formations include parts of the intertongued Wasatch, Green River, and Bridger Formations. These three Eocene strata are important, economically, for their energy, and metallic and nonmetallic resources, and for their abundance of fossil fauna and flora (Roehler, 1992).

The “thrust belt” (variously termed overthrust belt, Sevier fold and thrust belt, Sevier orogenic belt, fold and thrust belt, Wyoming thrust belt, and Wyoming-Idaho-Utah thrust belt in the cited literature) forms the western boundary of the Green River Basin on the western margin of Wyoming. Folding and thrust faulting occurred during the Cretaceous-to-Paleocene Sevier orogeny (~130–60 Ma) (Link and DeGrey, 2016).

In Utah, the study area is in Bear River Range (fig. 3) and the Wasatch Range (fig. 4). The Wasatch Range is a north-south oriented mountain range that extends from Idaho south to central Utah. The western flank is very steep and relatively straight as a result of displacement along the still-active Wasatch Fault. The eastern flank rises more gently. The Wasatch Range has a core of Archean quartzites, gneisses, and schists overlain by Mesozoic sandstones, shales, mudstones, and limestones (Moyle, 1981). Locally, Cenozoic conglomerates and shales, interspersed with volcanic tuffs and breccias, form the surface layers of strata (Moyle, 1981). By contrast to the Wasatch Range, the Bear River Range, located between Cache Valley and Bear Lake, is relatively small in area (Banner, 1992).

### Mining and Mineral Exploration Activity in the Study Areas

Recent mining and mineral activity in the study areas is sparse. Currently (2016), there are no active mines or mineral processing plants within the proposed withdrawal area.

Beyond the margins of the proposed withdrawal area, but inside the study area, there are uranium sites in the Great Divide Basin; iron at South Pass; and lode and placer gold at South Pass, Atlantic City, and Lewiston, Wyoming. Of the nearly 3,000 claims in the study areas, only 13 are active (table 1); all are placer claims, and all are in the Southwestern and South-Central Wyoming study area. All of these active claims fall within the area outlined in this report as having potential for lode or placer gold. There are no active claims in the Bear River Watershed study area; therefore, none of these active claims is within the proposed withdrawal areas. Table 1 shows the number and status type of all cases that intersect the proposed withdrawal area in a specific study area.

## Southwestern and South-Central Wyoming Study Area

### Past Mining Activity

There are 105 mine features shown on USGS 7.5-minute topographic maps of the Southwestern and South-Central Wyoming study area, of which 10 are adits, 14 are mineshafts, and 39 are prospect pits (Fernette and others, 2016b). These types of features are commonly associated with mining of locatable minerals and give a general indication of the extent of past mining activity in the area. The remainder of the mine features shown on the topographic maps are borrow pits and (or) gravel pits. The U.S. Geological Survey (USGS) Mineral Resource Data System (MRDS) database contains 20 records within the study area, which are reported as “producer” or “past producer” (U.S. Geological Survey, 2016). These include 18 with metallic minerals (predominantly gold) as the commodity and 2 with sand and gravel. MRDS contained no production data for these mines but the data do provide an indication of the level and nature of past mining activity. These MRDS records may include duplicates.

### Recent Mining Activity

The Wyoming Department of Environmental Quality permit data (Wyoming Department of Environmental Quality, 2015) were used to compile locations of active mines within the study area. Three active mine sites were found within the area. These included one gold mine and two sand

**Table 1.** Status and number of mining claims, mineral leases, mineral material sales sites, and 43 CFR 3809 surface management authorizations in the proposed withdrawal area within the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah.

[Source: Bureau of Land Management (BLM) LR2000 database, March 6, 2016. The number of cases is for the complete section that includes a proposed withdrawal area. ND, no data]

***A.*** Southwestern and South-Central Wyoming study area, Wyoming.

| Type | Mineral type | Number of unique cases | Active | Authorized | Pending | Closed | Cancelled | Expired | Rejected | With-drawn |
|---|---|---|---|---|---|---|---|---|---|---|
| Mining claims | locatable | 2,955 | 13 | ND | ND | 2,942 | ND | ND | ND | ND |
| Coal leases | leasable | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Geothermal leases | leasable | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Non-energy solid mineral leases | leasable | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Oil and gas leases | leasable | 468 | ND | 14 | 1 | 452 | 1 | ND | ND | ND |
| Mineral materials sales sites | salable | 11 | ND | ND | ND | 11 | ND | ND | ND | ND |
| Surface management 3809 plans | locatable | 18 | ND | ND | 1 | 17 | ND | ND | ND | ND |

***B.*** Bear River Watershed study area, Wyoming and Utah.

| Type | Mineral type | Number of unique cases | Active | Authorized | Pending | Closed | Cancelled | Expired | Rejected | With-drawn |
|---|---|---|---|---|---|---|---|---|---|---|
| Mining claims | locatable | 106 | ND | ND | ND | 106 | ND | ND | ND | ND |
| Coal leases | leasable | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Geothermal leases | leasable | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Non-energy solid mineral leases | leasable | 1 | ND | ND | ND | 1 | ND | ND | ND | ND |
| Oil and gas leases | leasable | 792 | ND | 29 | ND | 763 | ND | ND | ND | ND |
| Mineral materials sales sites | salable | 22 | ND | 3 | 1 | 16 | ND | 2 | ND | ND |
| Surface management 3809 plans | locatable | ND | ND | ND | ND | ND | ND | ND | ND | ND |

and gravel operations. According to the Wyoming Mines Inspector (Adcock, 2014), the South Marble Mine, owned by Sublette County Road and Bridge, produced 42,180 short tons of sand and gravel in 2014 (Fernette and others, 2016a). A sand and gravel operation, called 15 Mile Knoll and owned by Sweetwater County, is reported to be active (Fernette and others, 2016a). Lastly, although the Mary Ellen gold mine has an active permit, there is no report of activity or production in the annual report of the State Inspector of Mines of Wyoming (Adcock, 2014).

## Mine Production Data

Production data were found for 16 past-producing mines located within the study area (table 2). All are gold mines that are located in the South Pass-Atlantic City gold district, which is within the study area but outside the proposed withdrawal area. The exact activity dates for these specific mines are not provided, but the periods of active mining in the district are shown in table 2. Another mine, South Marble, recently produced sand and gravel.

The largest of the mines, the Carissa Mine (immediately northeast of the proposed withdrawal area), produced more than 53,000 troy ounces (troy oz) of lode gold before 1911 (Hausel, 1980). The study area, but not the proposed withdrawal area, also covers parts of the Rock Creek placer deposit, which produced 11,500 troy oz of placer gold from 1933 to 1953 (Hausel, 1991).

## Active Exploration

No site-specific information was found on active exploration projects within the study area. The Wyoming State Geological Survey (Wayne Sutherland, Wyoming Geological Survey, written commun., January 21, 2016) and the USGS Minerals Yearbook (U.S. Geological Survey, 2008, 2010, 2013) report that within the past 10 years, companies have conducted exploration in the Dickie Springs-Oregon Gulch gold placer area, which is within the southern part of the South Pass block of the study area.

One site within the study area was found to have reported resource data. The Carissa deposit (at the Carissa Mine) has a reported resource of 100,000 short tons, with an average grade of 0.368 troy oz of gold per ton based on exploration in 1994 (Fernette and others, 2016a). These values have been revised downwards from the 252,405 tons at 432 troy oz/ton reported in 1989 (Hausel, 1991, p. 47).

The southern part of the South Pass block (fig. 1) of the study area covers the eastern one-third of the Dickie Springs-Oregon Gulch gold paleoplacer area, which Love and others (1978) estimate may contain over 28 million [troy] oz of gold (Hausel, 1989).

**Table 2.** Production data for mines in the Southwestern and South-Central Wyoming study area.

[ND, no data; troy oz, troy ounce; NA, not applicable; Au, gold]

| Mine name | From | To | Commodities | Ore, in short tons | Au, in troy oz |
|---|---|---|---|---|---|
| Caribou Mine | ND | 1911 | Au | ND | 26,450 |
| Carissa Mine | ND | 1954 | Au | ND | 53,683 |
| Carrie Shields Mine | ND | 1911 | Au | ND | 1,850 |
| Diana Mine | ND | 1911 | Au | ND | 530 |
| Doc Barr Mine | ND | 1911 | Au | ND | 900 |
| Duncan Mine | ND | 1956 | Au | ND | 3,830 |
| Empire State Mine | ND | 1911 | Au | ND | 260 |
| Franklin Mine | ND | 1911 | Au | ND | 15,860 |
| Garfield (Buckeye) Mine | ND | 1911 | Au | ND | 21,150 |
| Ground Hog Group | ND | 1911 | Au | ND | 1,585 |
| Mary Ellen | ND | 1911 | Au | ND | 6,600 |
| Midas Mine | ND | 1911 | Au | ND | 1,380 |
| Rock Creek Placers | 1933 | 1953 | Au | ND | 11,500 |
| Rose Mine | ND | 1911 | Au | ND | 260 |
| Soules and Perkins Mine | ND | 1911 | Au | ND | 25,000 |
| South Marble | 2014 | 2014 | Sand and Gravel | 42,180 | NA |
| St. Louis Mine | ND | 1911 | Au | ND | 400 |

## Bear River Watershed Study Area

### Past Mining Activity

An initial estimate of the level of past mining activity was made by summarizing the number of mining-related features shown on USGS topographic maps of the study area (Fernette and others, 2016b). Of the 117 mine features shown on USGS 7.5-minute topographic maps within the study area, 13 are adits, 2 are shafts, 19 are open-pit mines, and 36 are prospect pits. These types of features are most commonly associated with mining of locatable minerals and give a general indication of the extent of past mining activity in the area. The other mine features shown on the topographic maps are borrow pits and (or) gravel pits.

A second estimate of past mining activity was made by extracting records for mines with a status of "producer" and "past producer" from the USGS Mineral Resources Data System (MRDS) database. The MRDS database contains 82 records within the study area that are reported as "producer" or "past producer" (U.S. Geological Survey, 2005). These include 5 that were mined for metallic minerals, 22 for phosphate, and 55 for stone or sand and gravel. MRDS contained no production data for these mines but the data provide an indication of the level and nature of past mining activity. Not all of these MRDS records are unique—some may be duplicate records.

### Recent Mining Activity

Permit data (Wyoming Department of Environmental Quality, 2015) were used to compile locations of active permits within the Wyoming part of the study area. For the Utah part of the study area, permit data from the Minerals Program of the Utah Division of Oil, Gas, and Mining (Utah Division of Oil, Gas, and Mining, 2016), and mine locations from the Utah Geological Survey's Utah Mineral Occurrence System (Utah Geological Survey, 2015) were used to locate active mines.

Fifteen active mine sites were found within the study area (Fernette and others, 2016b). Fourteen of these sites are for stone and (or) sand and gravel. The remaining site is the Kemmerer coal mine, which produces an average of 4.8 million tons of coal annually (Westmoreland Coal Company, 2016). No production data were found for any of the other active mines.

### Mine Production Data

No production data were found for any past producing mines located within the study area.

### Active Exploration

No information was found on active exploration projects within the proposed withdrawal area of the study area.

## Leasable

Leasable minerals, as defined by the Mineral Leasing Act of 1920 (30 U.S.C. 181 et seq.), include the subsets leasable fluid and solid minerals. Leasable fluid minerals include oil and gas and geothermal resources, and leasable solid minerals include coal, oil shale, native asphalt, phosphate, sodium, potash, potassium, and sulfur.

The potential for the occurrence within the study area of six leasable minerals (oil and gas, coal, geothermal, phosphate, potash, and trona) was evaluated. Of these commodities, only oil and gas and phosphate resources were identified in or near the study areas and are discussed in detail in this report.

With the exception of phosphate, no additional leasable minerals are known to have been produced or to occur in the study area. Phosphate was mined in the past from deposits adjacent to the study area at South Mountain, Leefe, Cokeville, and several small mines in the Wyoming part of the thrust belt. Sodium, in the form of trona (and converted to soda ash), is produced to the south and west of the study area but not within it. Potash occurs to the southwest of the study area, nearer to the Great Salt Lake, but is not present in the study area. An area near the Leucite Hills was prospected as a potential source of potassium; however, those deposits never proved feasible for mining. There is no record of native asphalt, sulfur, or bentonite in the area.

## Locatable

Locatable minerals are those for which the right to explore, develop, and extract on Federal land open to mineral entry is established by the location (or staking) of lode or placer mining claims (General Mining Act of 1872 [30 U.S.C. 22–42], as amended, or "Mining Law"). Locatable minerals are divided into metallic minerals, industrial minerals, and uncommon varieties of mineral materials. Examples of metallic minerals that have been historically mined and are currently being mined in the vicinity of the study area include gold, silver, copper, iron, and uranium. Examples of industrial minerals are certain types of limestone and dolomite.

Although no locatable commodities have been produced in significant amounts from the proposed withdrawal areas, four locatable commodities have been produced in significant amounts immediately adjacent to the proposed withdrawal areas in Wyoming. Uranium is being mined by in situ recovery methods to the southeast of the study area. Gold (from both orogenic-type vein deposits and from placers) was mined in the South Pass/Atlantic City/Lewiston area, and there are still a few active placers and possibly lode claims in the area. Iron was produced from the Atlantic City mine, to the northeast of the study area. Copper from a sedimentary-hosted copper deposit was produced in unknown quantity from the Griggs Mine, more than 25 km north of the study area. Although there are no mines within the proposed withdrawal area that are known to have produced ore, at least one similar mineral occurrence is within the study area: the Rock Creek Valley copper occurrence within the Fossil Basin block. A second copper prospect occurs south of the study area at Cockscomb (U.S. Geological Survey, 2016).

### Mineral-Potential Tracts

Mineral-potential tracts are outlined for specific deposit types (appendix 2). A summary of mineral potential and levels of certainty are shown in appendix 1. For orogenic low-sulfide gold-quartz veins there are four tracts. The first is rated high with certainty level D encompassing the South Pass and Lewiston areas. South of the Lewiston tract there is an extension with high potential but certainty level B, and beyond that, where the tract is buried under Tertiary rocks, the potential drops to moderate with certainty level A. For sediment-hosted stratabound copper deposits there is one tract with moderate potential and certainty level C. Tracts for sandstone roll-front uranium are rated moderate potential with certainty level B in the Big Sandy area and low potential with certainty level C in the Fontenelle area. There are two paleoplacer gold tracts: one is evaluated as having high potential with certainty level D in the Dickie Springs-Oregon Gulch area and the other as having low potential with certainty level A in the Sand Creek area. Potential for placer gold deposits is rated high with certainty level D in the South Pass area and moderate with certainty level C in the rest of the Sweetwater River drainage system, where there is placer potential. There is low potential with certainty level B, C, and D for diatreme-hosted diamond deposits in the Leucite Hills. Details of each of the tracts are discussed in the Locatable Minerals section of this report.

## Salable

Salable minerals, also referred to as mineral materials, are sand and gravel, aggregates, dimension stone, petrified wood, cinders, clay, pumice, and pumicite, as described under the Mineral Materials Act of 1947 (30 U.S.C. 601 et seq.) and the Surface Resources Act of 1955 (30 U.S.C. 611–614).

With the exception of sand and gravel, there are no known sources of salable minerals in the study area. Most of the sand and gravel deposits are in Quaternary unconsolidated deposits. As of March 6, 2016, there were only three approved mineral material authorizations for sand and gravel (two for sand and gravel, one for shale) and one site pending (for sand) in the proposed Bear River Watershed study area and none in the Southwestern and South-Central Wyoming study area (Dicken and San Juan, 2016b). All other previous mineral material authorizations for sand and gravel seem to be closed, but this is not quite in accordance with reports of a productive South Marble sand and gravel operation in the northeastern part of the Big Sandy block (table 2).

# Introduction

The U.S. Department of the Interior has proposed to withdraw approximately 10 million acres of Federal lands from mineral entry (subject to valid existing rights) from 12 million acres of lands defined as Sagebrush Focal Areas (SFAs) in Idaho, Montana, Nevada, Oregon, Utah, and Wyoming (for further discussion on the lands involved see Day and others, 2016).The purpose of the proposed action is to protect the greater sage-grouse (*Centrocercus urophasianus*) and its habitat from potential adverse affects of locatable mineral exploration and mining. To inform the decision on whether to withdraw the SFAs from mineral entry, the Bureau of Land Management requires a mineral-resource assessment be completed to identify mineral resources within the proposed withdrawal area. The USGS Sagebrush Mineral-Resource Assessment (SaMiRA) project was initiated in November 2015 and supported by the BLM to (1) assess locatable mineral-resource potential and (2) to describe leasable and salable mineral resources for the seven SFAs and Nevada additions.

The purpose of this report is to summarize the current status of locatable, leasable, and salable mineral commodities and assess the potential for the occurrence of locatable minerals in the Southwestern and South-Central Wyoming and Bear River Watershed study area in Wyoming and Utah. A mineral-potential assessment for these study area was done by the U.S. Geological Survey (USGS) as part of the USGS Sagebrush Mineral Resource Assessment (SaMiRA) project being undertaken for BLM. This report was prepared as required by the Federal Land Policy and Management Act of 1976 (Pub. L. 94–579; 90 Stat. 2743) for an application for withdrawal of lands. This report by the U.S. Geological Survey follows guidance provided in BLM Manual Sections 3031 (Bureau of Land Management, 1985) and 3060 (Bureau of Land Management, 1994) for mineral assessments and mineral reports. The information and interpretations provided herein relied on the best publically available data and information sourced from Federal and State agencies, academic literature, and company reports.

The methodology followed for this resource assessment is described in detail in Hammarstrom and Zientek (2016) and the classification scheme used is described in appendix 1. Key datasets included geophysics (Anderson and Ponce, 2016), geochemistry (appendix 3; also, Smith and others, 2016), remote sensing (Rockwell, 2016), and mineral occurrence data (Fernette and others, 2016a, b; U.S. Geological Survey, 2016). Resource assessment tracts are assigned high (H), moderate (M), or low (L) potential at certainty ratings D (available data provide abundant direct and indirect evidence to support or refute the possible existence of mineral resources) to A (available data are insufficient and (or) cannot be considered as direct or indirect evidence to support or refute the possible existence of mineral resources within the respective area) (appendix 1).

## Lands Involved

This report describes the mineral potential of a USGS study area that encompasses the proposed withdrawal areas in two Sagebrush Focal Areas: Southwestern and South-Central Wyoming and the Bear River Watershed in Wyoming and Utah. The area of interest ranges from southwestern Wyoming to northeastern Utah (fig. 1). Within this area there are two study areas—a 1,943 square kilometer ($km^2$) (480,180 acres) part of the Southwestern and South-Central Wyoming Sagebrush Focal Area and a 4,192 $km^2$ (1,035,789 acres) part of the Bear River Watershed Sagebrush Focal Area (fig. 2; table 3). Together, the proposed withdrawal areas within these larger focal areas cover 1,680 $km^2$ (415,173 acres), of which the BLM manages 1,475 $km^2$ (364,477 acres) in parts of Lincoln, Fremont, Sublette, and Sweetwater Counties, Wyoming, and Rich and Cache Counties, Utah. Surface management for the remaining lands is coded as Forest Service, Bureau of Reclamation, and private or unknown. The study area is the aggregation of all Public Land Survey System (PLSS) townships containing proposed withdrawal areas, which are a subset of the lands in the SFAs, as provided by the BLM (San Juan and others, 2016). These outer boundaries containing the proposed withdrawal areas are referred to as the "study area" in this report. The boundaries of the proposed withdrawal areas are presented in BLM (2105a) and amended in BLM (2015b).

**Table 3.** Acreage of Southwestern and South-Central Wyoming and Bear River Watershed study area, Wyoming and Utah.

[The study area refers to the outer boundary of the Public Land Survey System (PLSS) townships that contain proposed withdrawal areas. BLM, Bureau of Land Management]

| Subdivision (block) | Study area acreage | BLM acreage in study area | Proposed withdrawal area acreage | BLM acreage in proposed withdrawal area |
|---|---|---|---|---|
| Southwestern and South-Central Wyoming study area | | | | |
| South Pass | 181,898.31 | 140,075.72 | 58,175.16 | 58,175.16 |
| Continental Divide | 23,058.82 | 21,776.89 | 19,323.62 | 19,323.62 |
| Big Sandy | 228,417.89 | 181,707.56 | 58,522.25 | 58,511.58 |
| Boars Tusk | 46,805.28 | 32,270.86 | 2,449.01 | 2,449.01 |
| Subtotal | 480,180 | 375,831 | 138,470 | 138,459 |
| Bear River Watershed study area | | | | |
| Fontenelle | 230,330.26 | 194,070.97 | 79,307.32 | 79,307.32 |
| Fossil Basin | 303,169.43 | 175,747.47 | 31,939.98 | 31,939.98 |
| Bear Lake Plateau | 502,289.29 | 153,709.92 | 165,455.36 | 114,770.7 |
| Subtotal | 1,035,789 | 523,528 | 276,703 | 226,018 |
| Total | 1,515,969 | 899,369 | 415,173 | 364,477 |

### Southwestern and South-Central Wyoming Study Area

For ease of description in this report, each subarea, or block, of the study area has been assigned a geographic name (figs.1 and 2). The Southwestern and South-Central Wyoming study area is subdivided into South Pass, Continental Divide, Big Sandy, and Boars Tusk blocks. Bear River Watershed study area is subdivided into the Fontenelle, Fossil Basin, and Bear Lake Plateau blocks. The Bear Lake Plateau block is in Utah; all the other blocks are in Wyoming. These names are strictly for use in this report and do not reflect any official names used by BLM or other land-management agencies.

The Southwestern and South-Central Wyoming study area (figs. 1 and 2; table 3) covers 138,470 acres in parts of Fremont, Sublette, and Sweetwater Counties, of which 138,459 acres are managed by BLM. Most of the study area lies north of a band of lands across the State:

> . . . that is 40 miles wide; 20 miles to the north and south of the Union Pacific Railroad right-of-way known as the "railroad checkerboard lands" . . . Every other section of land for 20 miles on either side of the railroad right-of-way is privately owned. (Bureau of Land Management, 2012)

Most of the Southwestern and South-Central Wyoming study area is located in the Wyoming Basin Province (fig. 3), a structural basin covering southwestern Wyoming and extending into northeastern Utah and northwestern Colorado. The greater Green River Basin is bordered by the north-south trending Wyoming Range (fig. 3) of the thrust belt (fig. 4) on the west, by the northwest-southeast trending Wind River Range (fig. 3) on the north, by the Ferris Mountains (fig. 3) on the northeast, by the Rawlins Uplift and Sierra Madre (fig. 3) on the east, and by the Uinta Mountains (fig. 4) and Axial Basin Uplift on the south in Utah and Colorado respectively. In Wyoming, the Green River Basin is subdivided into three smaller basins that are separated by the Rock Springs Uplift. The Green River Basin is located on the west side of the uplift, the Great Divide Basin is located on the northeast side, and the Washakie and Sand Wash Basins are located on the southeast (Bureau of Land Management, 2012), outside the study area (fig. 4).

### Bear River Watershed Study Area

Straddling the Utah-Wyoming State line, the Bear River Watershed study area (figs. 1 and 2) covers 4,192 $km^2$ (1,035,789 acres) in parts of Lincoln County, Wyoming, and

Rich and Cache Counties, Utah, of which the BLM manages 276,703 acres in the actual proposed withdrawal area (table 3). Bear River forms a broad floodplain between the States (fig. 3).

Study area lands in Wyoming primarily are in the thrust belt (fig. 4). Lands in Utah are in the Wasatch Range and Bear River Range west of Bear River and south of Bear Lake (fig. 3).

## Organization of this Report and Terminology

The outline of this report is based on guidance published in the BLM Manual Sections 3060 and 3031 (Bureau of Land Management, 1985, 1994). To the extent possible, this report is organized to reflect BLM technical and legal language. Information is grouped by the legal classification of minerals recognized by BLM. Potential for occurrence is only discussed for locatable minerals.

Several schemes are used to classify types of minerals in scientific and technical literature. For example, a distinction is made between materials from which metals are extracted (**metallic**) from those that are not used as a source of metal or energy (**nonmetallic or industrial**). Another scheme differentiates material that is extracted from solid rock (**lode**) from that which was concentrated by moving water in sediment (**placer**). **Common variety minerals** do not possess a distinct or special value. **Uncommon variety minerals** have unique commercial value. **Strategic and critical minerals** are distinguished according to their importance to the Nation. Other classification schemes distinguish material based on the ultimate source of the valuable material—magma, hydrothermal fluid, surficial water, or weathered material.

The BLM differentiates **locatable, leasable, and salable minerals**; these terms are based on U.S. mining law and Departmental decisions and are not widely used in scientific literature. **Locatable minerals** in the United States are those that may be acquired under the Mining Law, as amended. Locatable minerals include metallic minerals, industrial minerals, and certain varieties of mineral materials if they are uncommon because they possess a distinct and special value. **Leasable minerals** refers to commodities acquired through the Mineral Leasing Act of 1920, 30 U.S.C. 181–287, as amended; the Geothermal Steam Act of 1970, 30 U.S.C. 1001–1026, as amended; or the Acquired Lands Act of 1947, 30 U.S.C. 351–359, as amended. Examples of leasable minerals include oil, gas, coal, oil shale, sodium, potash, phosphate, and all minerals within acquired lands. **Salable minerals** on Federal lands are those sold by sales contract from the Federal Government, and by free use permit to governmental agencies and nonprofit organizations. The applicable statute is the Mineral Materials Act of 1947, 30 U.S.C. 601–604, as amended. Salable minerals are generally common varieties of materials; examples include construction materials and aggregates, such as sand, gravel, cinders, roadbed, and ballast material.

Rights to locatable minerals are established by the location (or staking) of lode or placer mining claims. Acquisition of leasable minerals is by application for a Government lease and permits to mine or explore after lease issuance. Salable minerals on Federal lands are sold by sales contract. Surface disturbance associated with locatable mineral development must be approved and permitted according to Surface Management regulations (43 CFR 3809). Table 1 summarizes information on mining claims, leases, and salable mineral sites, along with surface management permits in the study areas.

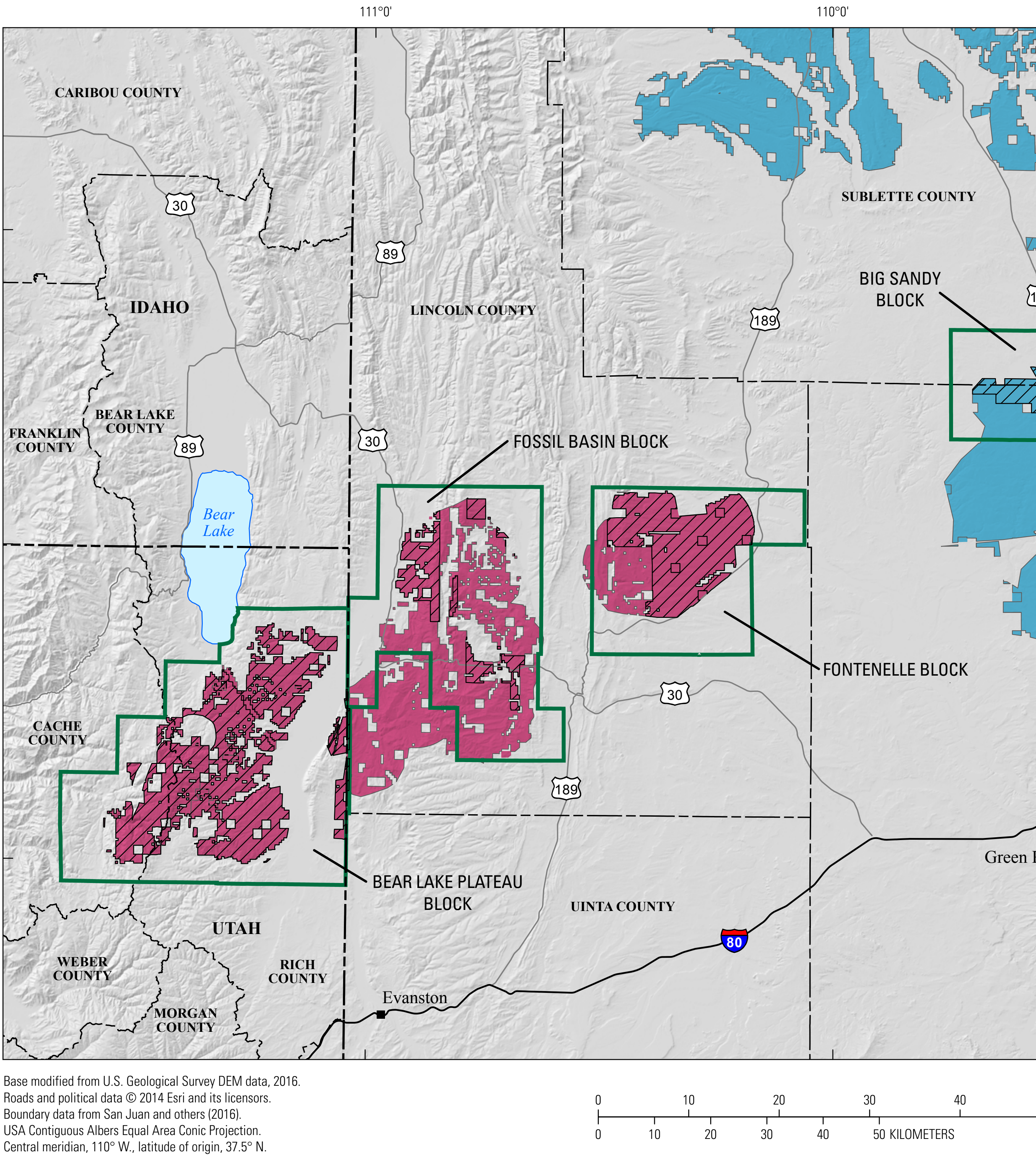
The mining laws applicable to Federal lands of the United States were not developed with specific knowledge of geology and types of mineral materials. Even so, the various legal types of minerals do have some broad geologic associations. Leasable minerals include areally extensive types of valuable earth materials most commonly occurring in sedimentary basins: oil and gas fields, coal fields, oil shales, large bedded deposits of soluble sodium and potassium salts, and large bedded deposits of phosphorite. Salable minerals are common, widely distributed earth materials with low unit value. They must be obtained near where the need exists. If the material is not leasable or salable, it is locatable. Most, but not all, of this type of material occurs in spatially restricted areas.

A glossary of terms is provided in chapter A (Day and others, 2016), the companion report to this assessment. In some parts of this report, a brief discussion is provided to clarify usage of specific terms and to relate how concentrations of valuable earth materials form to the legal definitions that determine their ownership and development. However, for other terms, like "minerals," the intended meaning must be inferred from context.

## Who Did the Work?

This report represents contributions from a multidisciplinary team of USGS geologists, geophysicists, geochemists, mineral-commodity specialists, and geographic information system (GIS) experts. These geoscientists reached out to personnel from the Wyoming State Geological Survey and the Utah Geological Survey to gather the most recent geologic and mineral resource information available. Representatives from these groups also provided helpful feedback on the preliminary tracts that we developed for the study area.

Anna Burack Wilson and Timothy Hayes wrote the majority of the text in this report. Tim took the lead on the major mineral deposit models for which tracts were drawn, whereas Anna compiled the salable and other commodities while stitching the rest of the manuscript pieces together. Doug Yager wrote the section on geology, and it was revised by both Mary Ellen Benson and Anna. John Horton and Stuart Giles, in Denver, Colorado; Heather Parks, in Spokane, Washington; and Connie Dicken, in Reston, Virginia, undertook much of the GIS work that underpins this report. John constructed the digital tracts in this report, and Stuart produced most of the figures from the GIS. Connie also compiled and delivered information from BLM, and helped us to understand its meaning and significance. The "Leasable Minerals" section




Base modified from U.S. Geological Survey DEM data, 2016.
Roads and political data © 2014 Esri and its licensors.
Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

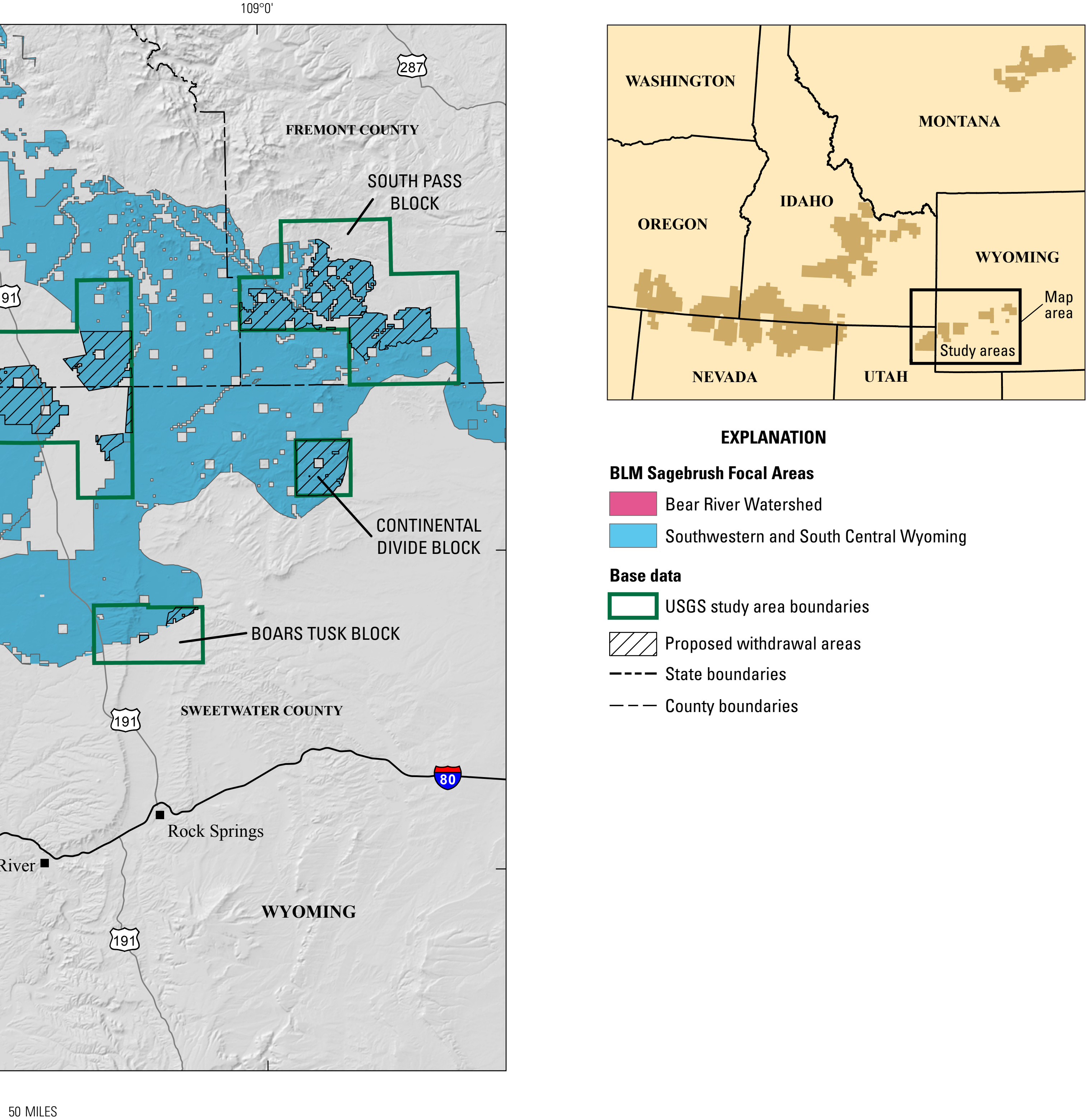
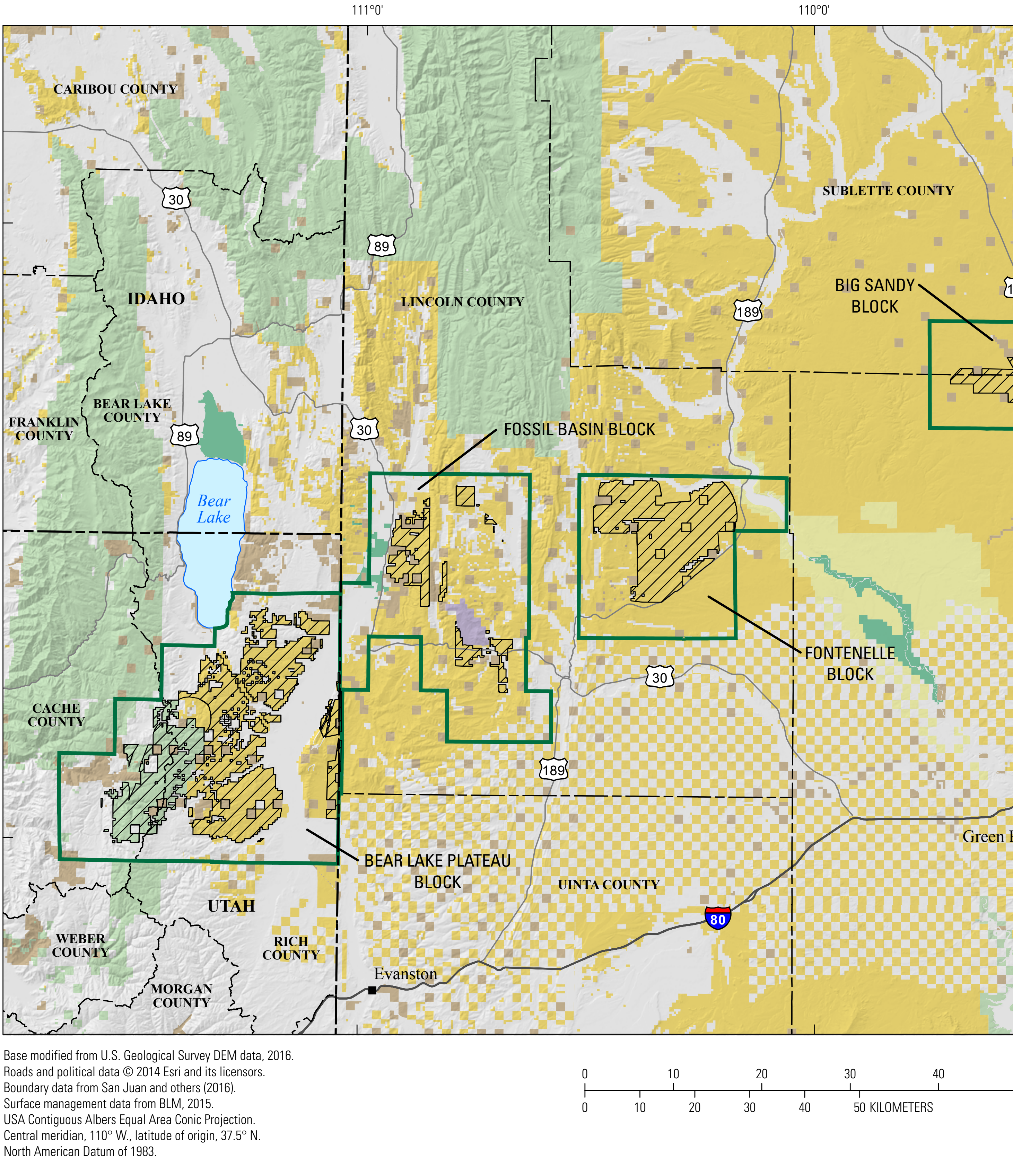



**Figure 1.** Map showing the Southwestern and South-Central Wyoming and Bear River Watershed Sagebrush Focal Areas, Wyoming and Utah, and U.S. Geological Survey (USGS) study area boundaries. Darker areas on the inset map depict all of the study areas in six western states. BLM, Bureau of Land Management.

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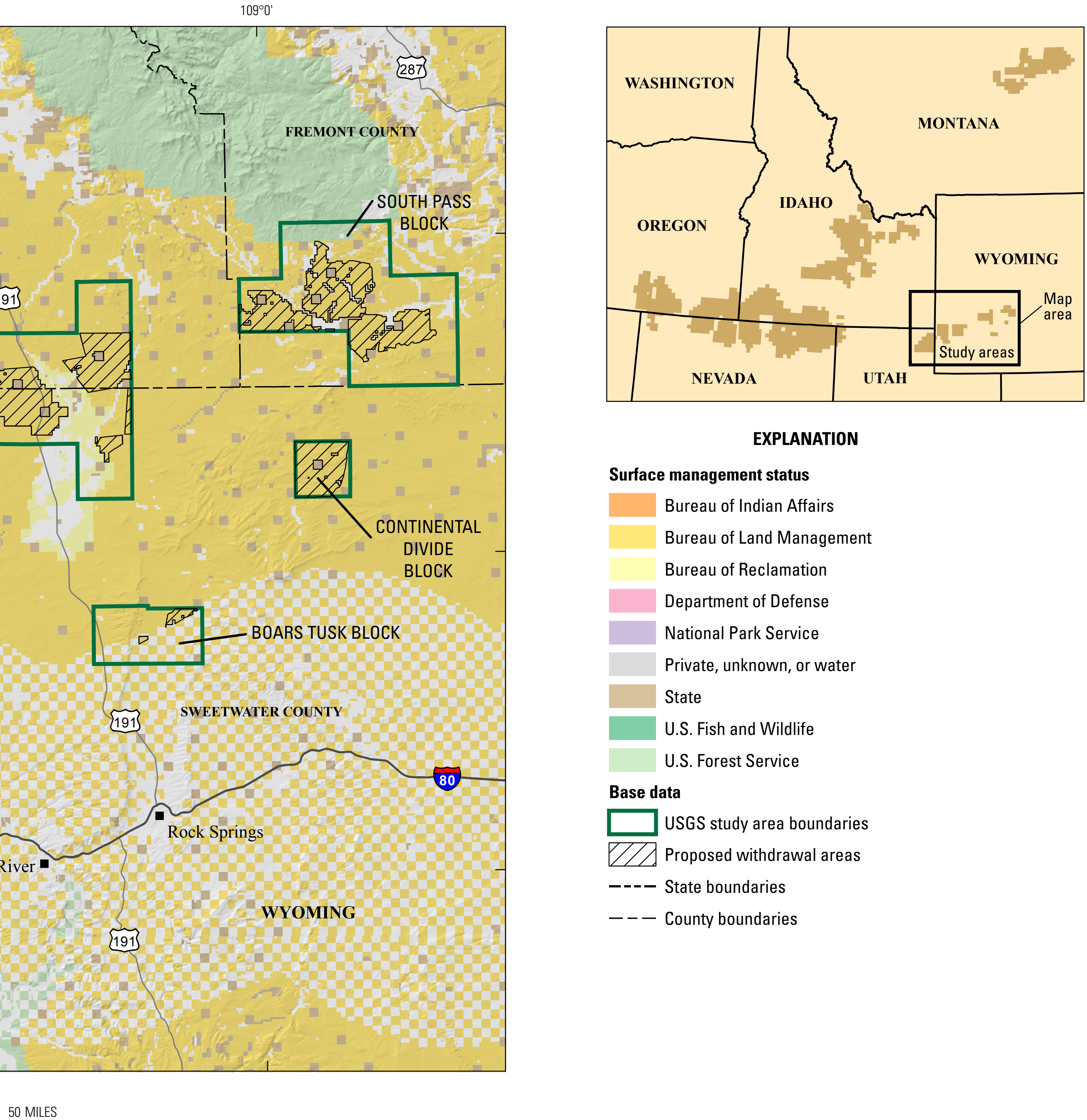
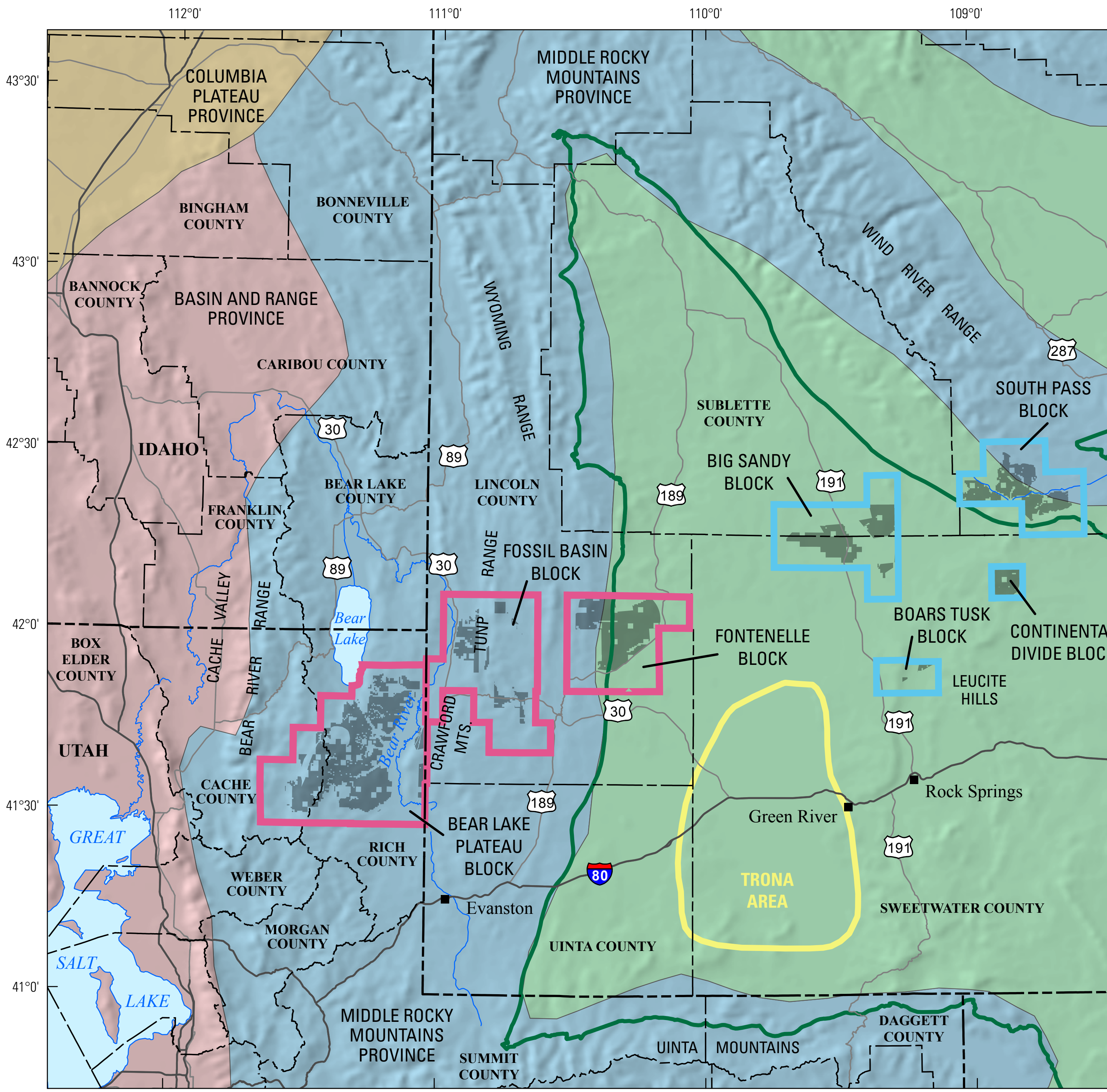



**Figure 2.** Surface land-management map of the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.




Base modified from U.S. Geological Survey DEM data, 2016.
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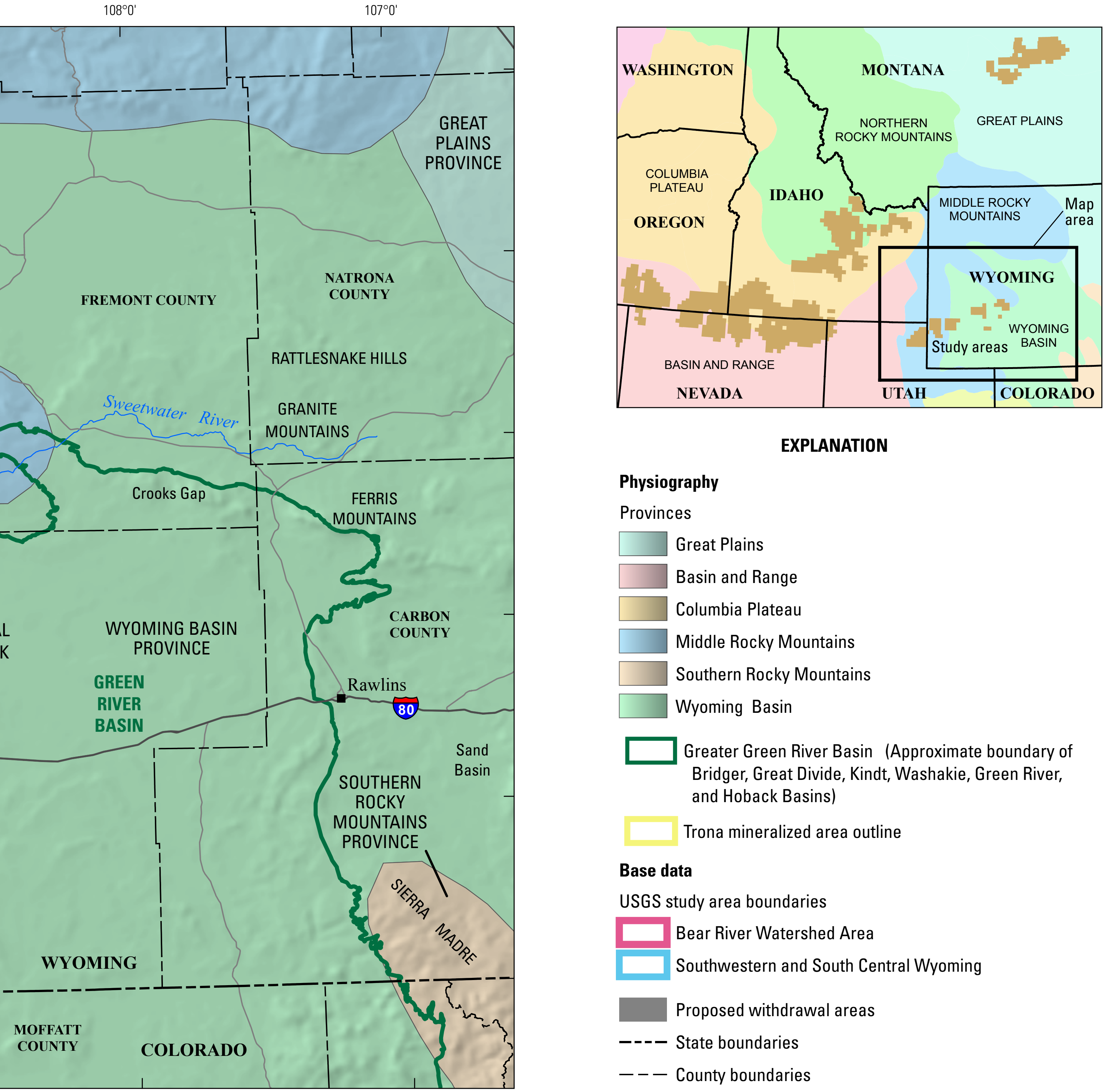
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS




Green River Basin data from USGS Southwest WY Province Assessment Team, (2005a).
Trona area from Fernette and others (2016).
Physiographic provinces from USGS (2014).

**Figure 3.** Map showing the physiography of the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.

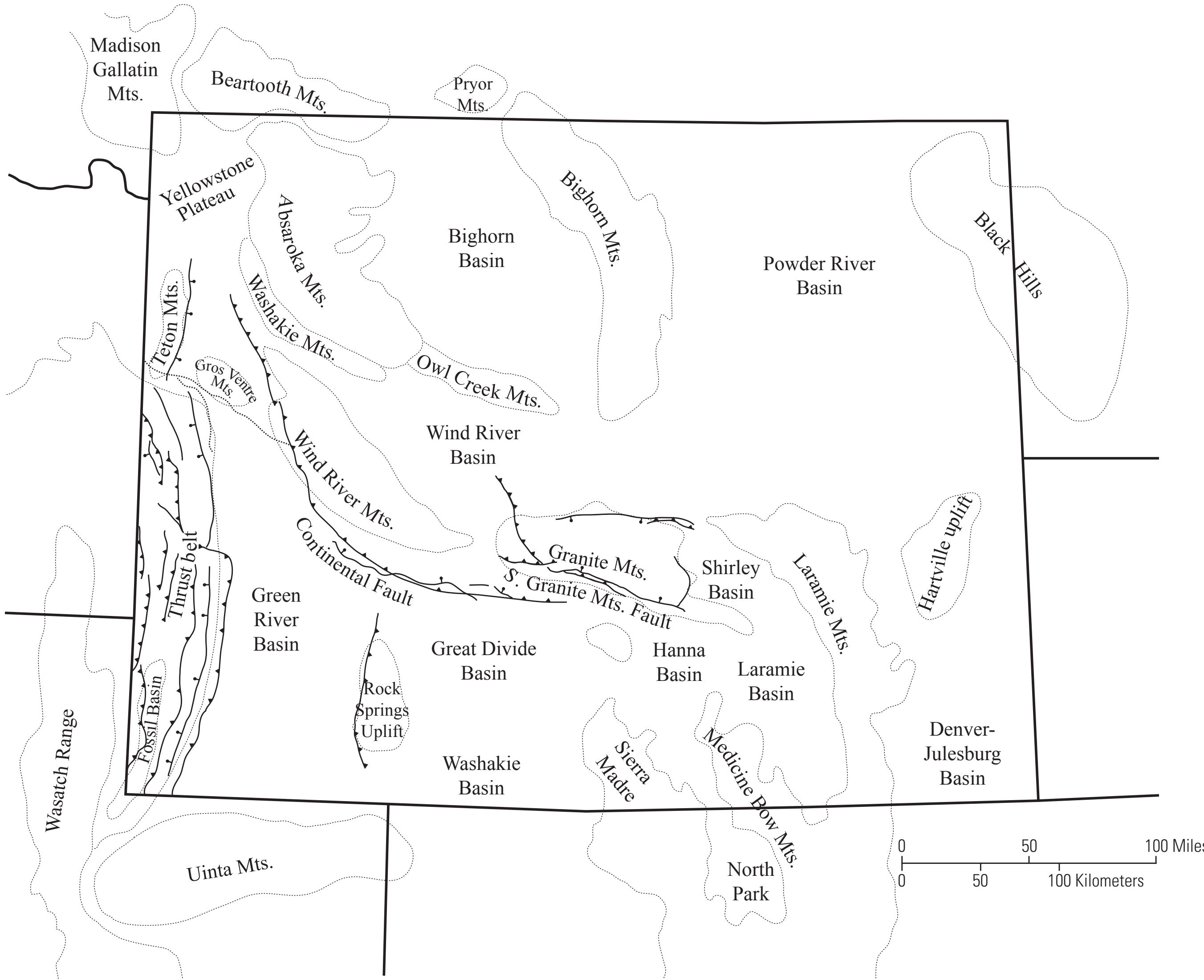



**Figure 4.** Map showing the geologic and tectonic setting, with mountain ranges and structural basins (dotted lines), in Wyoming and surrounding areas (modified from Roberts, 1989). Faults (solid lines) are generalized from Snoke (1993) for southwest Wyoming (bar and ball on down-dropped block of normal fault; teeth on upper plate of thrust fault).

of this report was produced by several authors—Ronald Drake wrote the "Oil and Gas" section; Colin Williams, Jonathan Glen, and Jacob DeAngelo wrote the "Geothermal Energy" section; Jon Haacke wrote the "Coal" section; Mary Ellen Benson wrote the "Phosphate" section; and Doug Yager wrote the "Potash" section. Eric Anderson compiled the geophysical results in this report, and he also compiled the simplified geologic map for Doug Yager to illustrate the geologic framework. Barnaby Rockwell provided expert knowledge of remote sensing data, which helped to inform and validate the tracts, especially for sandstone roll-front uranium. Greg Fernette made available the preliminary version of U.S. Geological Survey Mineral Deposit Database project (USMIN) and provided helpful feedback about past production and possible resources in the study area. Don Bleiwas provided the market-demand commodity profiles that are referenced in this report.

# Description of Geology

A general geologic and tectonic history for Wyoming and northeastern Utah is presented in this section to provide context for discussions of mineral tracts delineated as part of this report. The diverse physiography of uplifted mountain blocks, adjacent intermountain basins, and sinuous folded and thrusted mountain ranges in the study area is a result of a long and complex geologic history of the study area. Geologic maps of Wyoming (Love and Christiansen, 1985; Green and Drouillard, 1994) and Utah (Hintze, 1980; Hintze and others, 2000) provide additional geologic background.

This section summarizes, from oldest to youngest, the geologic history of the area. It is beyond the scope of this report to discuss all rock units within each geologic period.

Selected formations are discussed as they pertain to important geologic or tectonic events or are of economic interest.

## Physiography

Most of the study areas covered in this report are in the Wyoming Basin (physiographic) Province (fig. 3) (Sullivan, 1980). The Wyoming Basin includes all or parts of the Green River, Great Divide and Washakie Basins, and the Rock Springs Uplift (figs. 3 and 4). This province is made up of high plains and plateau areas and is bordered by mountain ranges and major uplifts of the Middle Rocky Mountains Province. The southern end of the Wind River Range extends into the South Pass block of the Southwestern and South-Central Wyoming study area on its northern border. Surface features reflect erosion by wind and water in an arid, cold-temperature environment. In some instances, they have been modified by faulting or volcanic activity (Bureau of Land Management, 2012).

## Regional Geology and Tectonic Setting

The geologic history of the study area spans nearly 4 billion years from Archean through the Holocene. Archean and Proterozoic rocks (together, the Precambrian) are present in the Wind River Range north of the study area and around Atlantic City and South Pass in the northeastern part of the study area. Much of the Paleozoic section is exposed in the thrust belt in western Wyoming. Mesozoic sedimentary rocks fill the basins. Cenozoic rocks blanket the landscape, especially along waterways. A generalized geologic map of the study area is shown in figure 5.

The Southwestern and South-Central Wyoming study area extends from the southwestern side of the Wind River Mountains, a northwest-trending basement uplift, which is composed of Archean gneisses and granites that were thrust westward over Paleozoic and Mesozoic sedimentary rocks in the Late Cretaceous through Eocene Laramide orogeny (Frost and others, 2000) and southwestward into the northern greater Green River Basin, a sedimentary basin also formed during the Laramide orogeny (Ryder, 1988). The Bear River Watershed study area extends from the northern Green River Basin across the thrust belt to the eastern boundary of the Basin and Range Province in northern Utah (fig. 3).

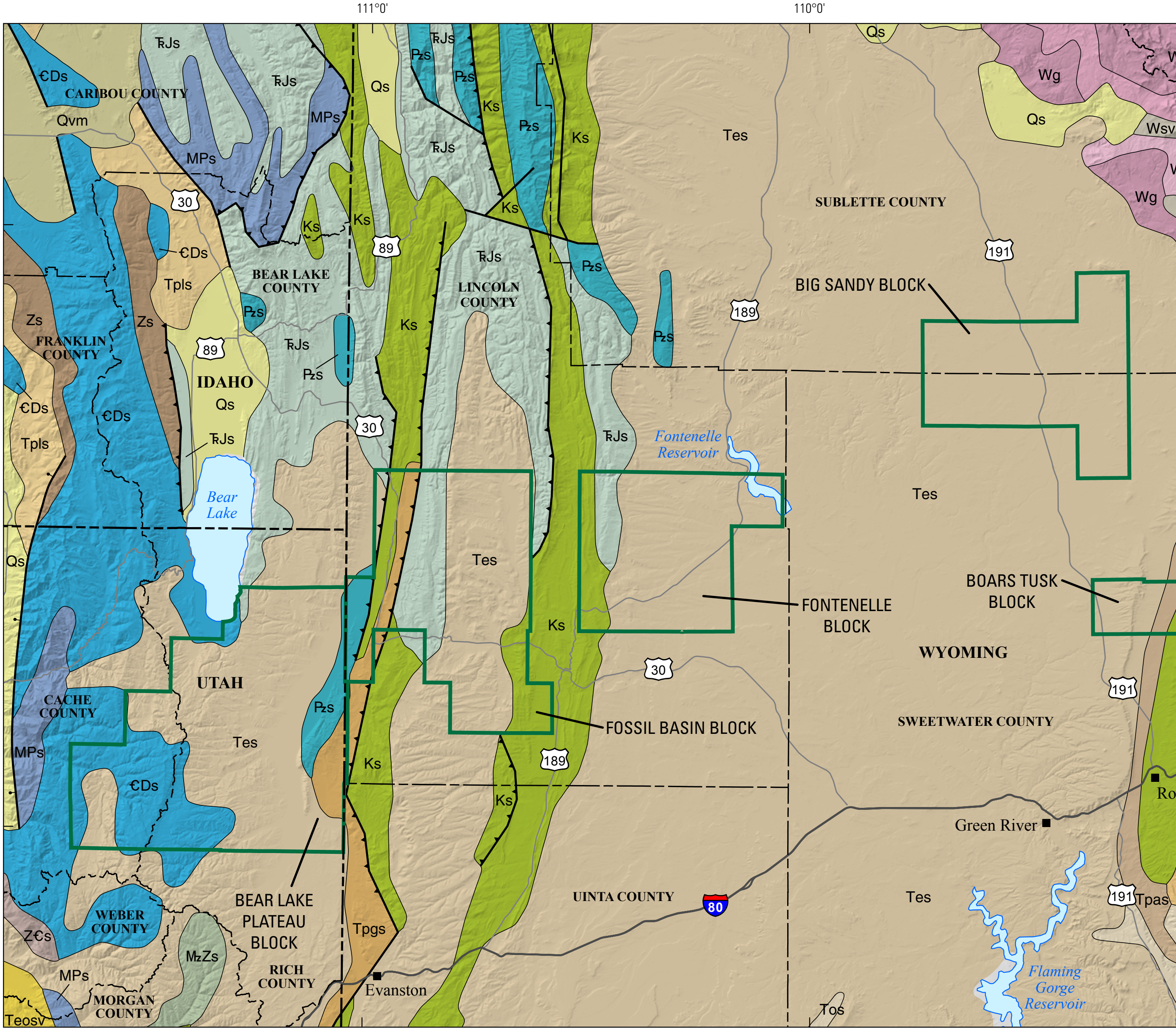
### Archean and Proterozoic Rocks

Some of the oldest known Archean rocks of the North American craton (Laurentia) underlie much of Wyoming (Snoke, 1993). Basement-cored Laramide uplifts provide excellent bedrock exposures of these rocks. The Precambrian history of Wyoming is characterized by continental-arc-magmatism terrane accretion that formed the continental craton named the Wyoming Province (Mueller and Frost, 2006). Subduction along the southern margin of the Archean Wyoming craton during the Proterozoic resulted in accretion of oceanic island arc terranes along a tectonic suture zone named the Cheyenne belt (Karlstrom and Houston, 1984; Jones and others, 2010). This zone of tectonism was a zone of crustal weakness that was subsequently intruded by mafic (low $SiO_2$) to felsic (high $SiO_2$) composition magmas during the Mesoproterozoic. A billion-year gap in the geologic record occurred between the Mesoproterozoic and the Phanerozoic (Snoke, 1993). The Proterozoic gap is known throughout the world as the Great Unconformity and is characterized by erosion of the ancient continental crust and sedimentation that occurred throughout this area, and globally (Peters and Gaines, 2012). The gap in the geologic record is shorter in some places west of Laurentia and east of the thrust belt. Areas of younger Proterozoic terrain are identified in central Idaho and western Montana, as well as in southern Idaho and northern Utah (Foster and others, 2006). Precambrian basement in northeast Utah consists of Paleoproterozoic rocks of the Mojave Province (Yonkee and Weil, 2011). Neoproterozoic rocks are exposed in Utah north of the study area in the Bear River Range northeast of Bear Lake.

A fragment of an Archean greenstone belt exposed in the southern Wind River Range is of economic importance (Bayley and others, 1973). The greenstone belt is composed of variably metamorphosed, mafic to ultramafic volcanic rocks and associated sedimentary rocks. Greenstone is named for the greenish hue caused by such minerals as chlorite and green amphibole. Gold deposits, discovered between 1867 and 1871, occur in greenstone of the Miners Delight Formation metagraywacke at South Pass (Bayley and others, 1973). Banded-iron deposits in metasedimentary rocks of the Goldman Meadows Formation have been mined near South Pass (Bayley and others, 1973).

### Paleozoic Rocks

Lower- to middle-Paleozoic rocks (units MPs, ЄDs, and P̶zs, upper part of unit ZЄs on fig. 5) form a thin sedimentary veneer on Precambrian basement rocks. Where Precambrian basement rocks were uplifted during Paleozoic mountain building that formed the Pennsylvanian-Permian ancestral Rocky Mountains, Paleozoic rocks were eroded exposing Precambrian-cores of the uplifts. The Sierra Madre and Medicine Bow Mountains (fig. 4) are the northern-most manifestation of the ancestral Rocky Mountains, which extended southward from Wyoming into Colorado. Continentally derived sediments of the Upper Mississippian to Middle Pennsylvanian Amsden Formation (fig. 6) were eroded from uplifted crustal blocks and deposited in adjacent basins (Snoke, 1993). Pennsylvanian-age rocks unconformably overlie Precambrian-cored uplifts where older Paleozoic strata had been eroded during mountain building. An unconformity separates clastic terrestrial Pennsylvanian deposits from overlying Permian marine sedimentary strata. Permian marine rocks of the Phosphoria Formation (fig. 6) in central and western Wyoming are composed of phosphatic shale, phosphorite, and bedded




Base modified from U.S. Geological Survey DEM data, 2016.
Roads and political data © 2014 Esri and its licensors.
Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

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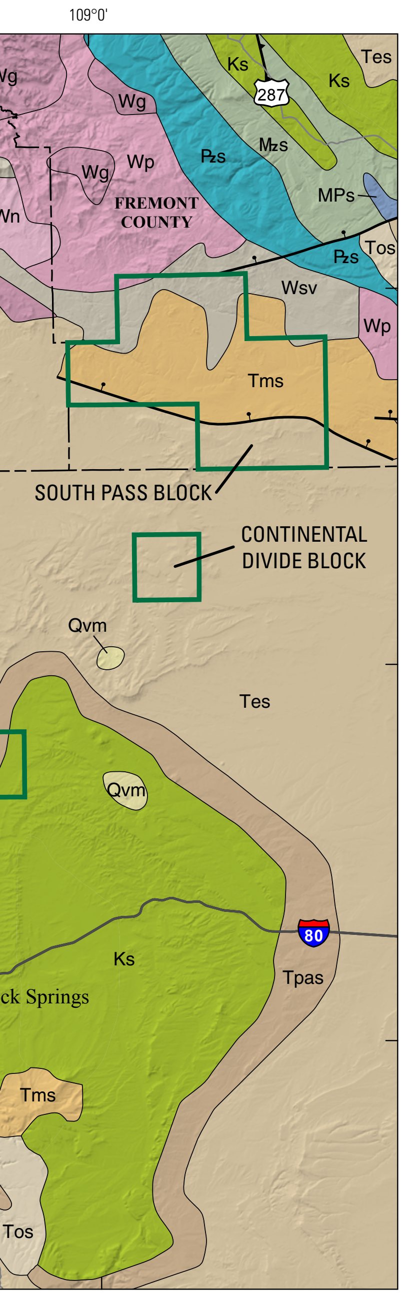
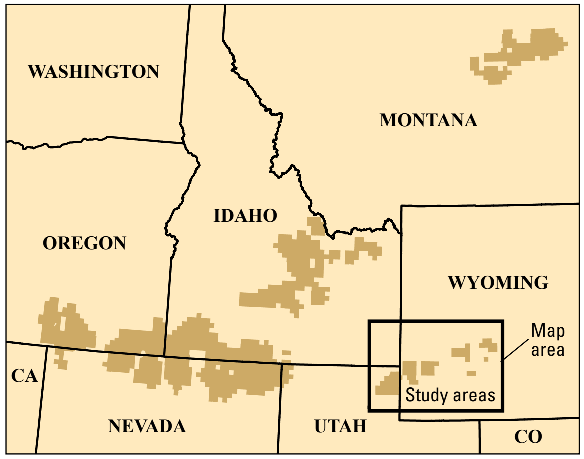



Geologic data from Garrity and Soller (2009).




**EXPLANATION**

**Lithostratigraphy**

- Qs — Quaternary sedimentary rocks
- Qvm — Quaternary mafic volcanic rocks
- Tpls — Tertiary (Pliocene) sedimentary rocks
- Tms — Tertiary (Miocene) sedimentary rocks
- Tpgs — Tertiary (Paleogene, includes Paleocene, Eocene, and Oligocene) sedimentary rocks
- Tos — Tertiary (Oligocene) sedimentary rocks
- Teosv — Tertiary (Eocene and Oligocene) interlayered sedimentary and volcanic rocks
- Tes — Tertiary (Eocene) sedimentary rocks
- Tpas — Tertiary (Paleocene) sedimentary rocks
- Mzs — Mesozoic sedimentary rocks
- Ks — Cretaceous sedimentary rocks
- TRJs — Triassic and Jurassic sedimentary rocks
- Pzs — Paleozoic sedimentary rocks
- MPs — Mississippian through Permian sedimentary rocks
- €Ds — Cambrian through Devonian sedimentary rocks
- Z€s — Neoproterozoic and Cambrian sedimentary rocks
- Zs — Neoproterozoic sedimentary rocks
- Wg — Late Archean granitic rocks
- Wp — Late Archean intermediate plutonic rocks
- Wn — Late Archean gneissic rocks
- Wsv — Late Archean interlayered sedimentary and volcanic rocks

**Structure**

- Formation contact
- Normal fault
- Thrust fault
- Unclassified fault

**Base data**

- USGS study area boundary
- State boundaries
- County boundaries

**Figure 5.** Simplified geologic map of the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. Geologic units simplified from Garrity and Soller, 2009. USGS, U.S. Geological Survey.

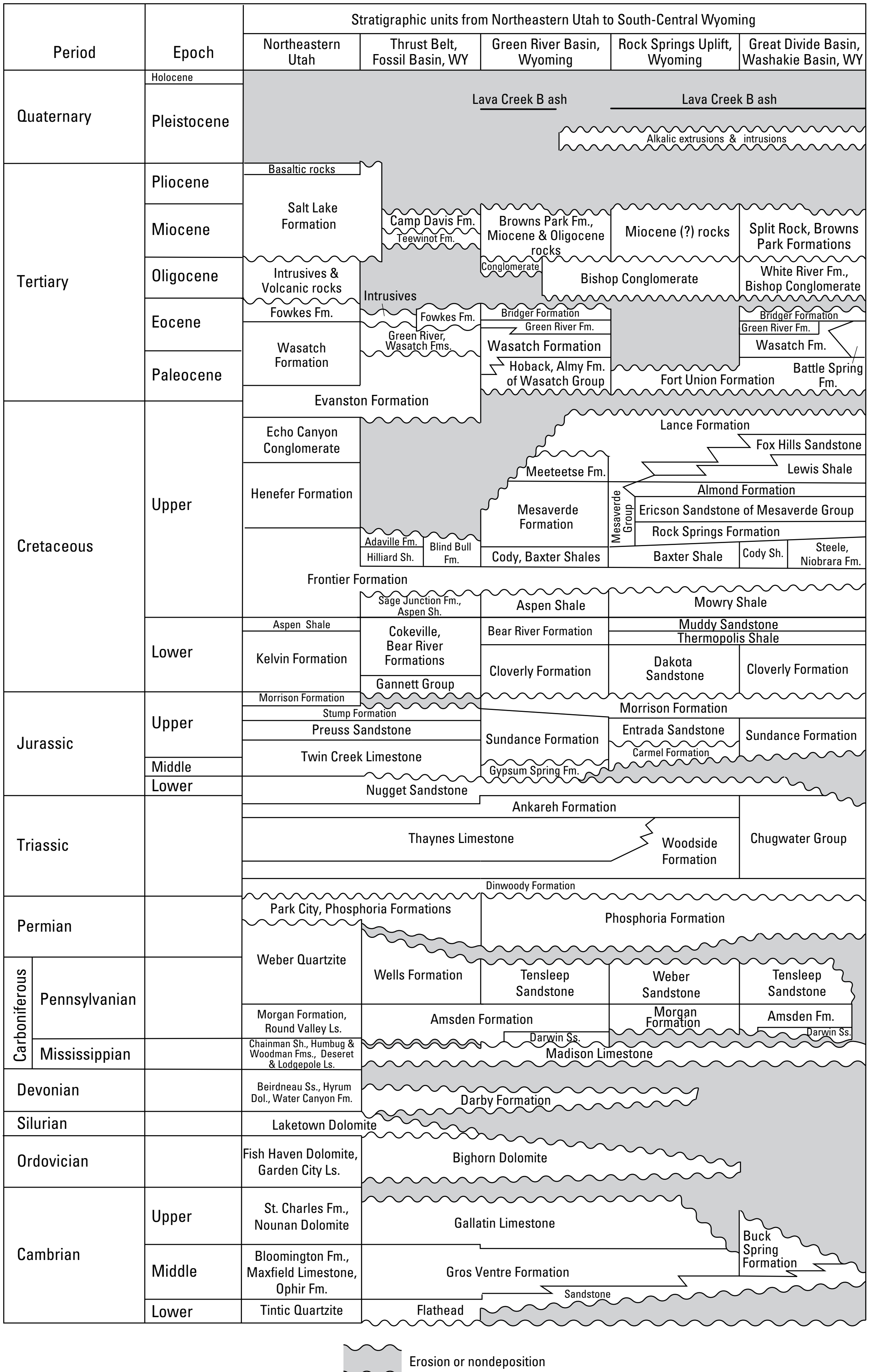



**Figure 6.** Stratigraphic chart of Phanerozoic rock units for the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah (compiled from Love and others, 1993; and Hintze and others, 2000). Fm., Formation; Ls., Limestone; Ss., Sandstone; Sh., Shale; Dol., Dolostone.

chert, and are a significant source of phosphate (Snoke, 1993). Where organic-rich, the Phosphoria Formation is a hydrocarbon source rock.

The Paleozoic history in northeastern Utah is recorded in marine, lower Paleozoic limestone, dolomite, and quartzite that form the Bear River Range, east and south of Bear Lake. Lower Paleozoic rocks also crop out along the thrust belt at the border with Wyoming. The dolomite may have economic potential and will be discussed later in the report.

## Mesozoic Rocks

Mesozoic strata were unconformably deposited on an eroded, stable platform of the continental western interior. Mesozoic rocks are represented by units Mzs, Ks, and TRJ on figure 5. In Wyoming, Triassic rocks are mainly exposed adjacent to uplifts along basin margins and in the Sevier fold and thrust belt (fig. 4). Triassic red beds of the Chugwater Group (fig. 6), composed mainly of siltstone, very fine-grained sandstone, and intertonguing limestone, were deposited in a tidal flat environment. Marine siltstone and limestone of the Dinwoody and Thaynes Formations (fig. 6) that are contemporaneous with deposition of the Chugwater Group to the east were deposited in western Wyoming. The Jurassic, aeolian Nugget Sandstone (fig. 6) was widely distributed throughout northeastern Utah, and western and south-central Wyoming. It is equivalent in age to other continental interior, ancient dune-sand deposits such as the Navajo Sandstone of the Colorado Plateau. The Nugget Sandstone has historically been a target for hydrocarbons in Wyoming and locally may host copper deposits. Terrestrial lacustrine and fluvial deposition of the Morrison Formation during the Late Jurassic, consisted of variegated, green to gray claystone, siltstone, silty sandstone and conglomerate and followed incursion of a shallow sea that was the precursor to the Cretaceous continental interior seaway.

Jurassic units, including the terrestrial Nugget Sandstone and marine Preuss Sandstone and Twin Creek Limestone, are exposed along the eastern margin of Bear Lake, in Utah.

## Cretaceous Rocks

A Middle Cretaceous seaway inundated much of the continental interior of the United States including much of Wyoming (Blakey, 2011). The seaway deposited marine sediments along the eastern margin of the Rocky Mountain Cordillera and in basins within or adjacent to the Southwestern and South-Central Wyoming study area. Cretaceous rocks deposited in the foreland basin east of the Rocky Mountain Cordillera are mainly shale, siltstone, sandstone, and conglomerate (unit Ks on fig. 5).

Lower Cretaceous rocks unconformably overlie the Jurassic Morrison Formation and include two episodes of marine to nonmarine sequences. The first sequence is represented by the Bear River Formation marine shale, limestone, and sandstone and the age-equivalent Dakota Sandstone. The second sequence, marked by deposition of the marine Mowry Shale, conformably overlies the Dakota Sandstone (Ryer and others, 1987). A sequence of marine to nonmarine sandstone and shale, the Upper Cretaceous Frontier Formation, was deposited unconformably on the eroded Mowry Shale surface. Marine to nonmarine Upper Cretaceous strata of the Baxter, Steele, Niobrara, and Cody Shales were deposited on the Frontier Formation. Nonmarine to near-shore marine, sandstone, and shale units (Mesaverde Group including Almond Formation, Lewis Shale, Fox Hills Sandstone, and Lance Formation) cap the Upper Cretaceous sequence. Cretaceous sedimentary rocks do not occur in northeastern Utah because the Cretaceous seaway did not inundate this area (Blakey, 2011).

Late Cretaceous east-west compressive stresses were caused by subduction of oceanic crust beneath continental crust of western North America. Subduction-related (arc) magmatism formed along the western margin of North America above the subducting oceanic slab. Volcanic eruptions along the magmatic arc resulted in volcanic ash being transported eastward and deposited in Cretaceous basins in Wyoming. These volcanic ash deposits were later converted through burial and diagenesis into bentonite (rock composed of smectite group clay minerals), which has a number of economic uses such as an additive to drilling-mud additive and sorbent for environmental contaminants. There are no known occurrences of bentonite in the study area.

Another manifestation of compressional tectonics during the Late Cretaceous is an area of mountain building known as the Sevier orogenic belt. The belt forms a sinuous fold and thrust belt along much of the border of western Wyoming and into northeastern Utah (figs. 4 and 5; Yonkee and Weil, 2015). The thrust faults transported Proterozoic to Mesozoic rocks eastward in an area that had been the passive margin of western North America, inland from the active volcanic arc to the west. This period of compressional tectonics continued as part of the Laramide orogeny from the Late Cretaceous to the Eocene. Before Laramide deformation, Upper Cretaceous marine shale was relatively continuous across southwestern Wyoming. However, the depositional continuity of the marine strata was interrupted during the Laramide orogeny as basement-cored mountains with extreme topographic relief and deep intermountain nonmarine basins formed (Snoke, 1993; Fan and Carrapa, 2014). The topographic relief developed at that time set the stage for a period of erosion and deposition of thick sequences of sediments in subsiding basins (Love, 1960). The transition in tectonic regime is recorded in basins where marine Lewis Shale (fig. 6) is overlain by thick terrestrial sedimentary rock sequences of Late Cretaceous to early Eocene strata. Terrestrial nonmarine continental basin rocks include the Upper Cretaceous Lance Formation (fig. 6), Paleocene coal-bearing Fort Union Formation, and Eocene Wasatch Formation (Snoke, 1993). Extensive deposits of the Wasatch and Evanston Formations (undivided) occur in the Bear Lake Plateau in northeastern Utah.

The lower Eocene arkosic, and locally conglomeratic, sandstone of the Battle Spring Formation in Wyoming is economically important for uranium mineralization. The uplifted Granite Mountains were a source of both sediment and uranium; uranium occurs in tabular, sandstone roll-front uranium deposits in the Battle Spring Formation (Wilson, 2015). Crooks Gap in the western Granite Mountains is an example of this style of uranium mineralization (Stephens, 1964). Sandstone roll-front uranium deposits are discussed and assessed later in this report.

## Eocene Magmatism and Contemporaneous Lake System

Paleogene magmatism in Wyoming is recorded in a group of chronologically and compositionally diverse igneous centers scattered throughout the State. Igneous rocks synchronous with the episode of Laramide tectonism include iron-rich, alkalic intrusions and lava flows in the Black Hills (in western South Dakota, not shown on figures in this report) (Snoke, 1993). Post-Laramide Eocene magmatic centers include the Rattlesnake Hills (fig. 3) north of the Granite Mountains (Hoch and Frost, 1993) and the Absaroka volcanic field in northwestern Wyoming (Smedes and Prostka, 1972). The Rattlesnake Hills are characterized by alkaline to subalkaline plugs, dikes, and flows; igneous rocks of the Absaroka volcanic field are mostly calc-alkaline intermediate- to felsic- composition lava flows and volcanoclastic rocks covering 23,000 $km^2$ (Smedes and Prostka, 1972; Feeley, 2003).

A widespread lake system (Lake Gosiute) developed contemporaneously with mid-Eocene magmatism. The lake is thought to have formed when an earlier eastward-flowing drainage system was cut off by westward tilting of the Wyoming foreland (Snoke, 1993). Although lakes developed in other parts of Wyoming during this time, Lake Gosiute was established in southwestern Wyoming in the areas of the Green River and Washakie basins (fig. 4). Sedimentary lake deposits are represented by the Tipton Shale, Wilkins Peak, and Laney Members of the Green River Formation (fig. 6). Members of the Green River Formation are thought to have developed in conditions in which lake water became chemically stratified and did not mix. These conditions contributed to precipitation of continuous stratiform beds of trona ($Na_3(CO_3)(HCO_3){\cdot}2H_2O$) and oil shale (organic-rich carbonate and siliceous mudstone) (Jagniecki and Lowenstein, 2015). The mineral trona is economically important in Wyoming and is used in manufacturing of glass, detergents, and textiles. The Green River Basin trona deposit (fig. 3), located beyond the study area west of the Rock Springs Uplift, is the largest known occurrence in the world.

The early Oligocene was characterized by deposition of volcaniclastic rocks and fluvial sediments of the White River Formation (fig. 6) deposited unconformably on an Eocene erosion surface. The volcanic debris is thought to be derived from volcanic activity in the Great Basin to the west (Snoke, 1993). Deposition of the White River Formation marked the end of an extensive episode of Eocene erosion (Epis and Chapin, 1975; Snoke, 1993).

## Neogene Extensional Faulting and Volcanism

Some preexisting Laramide-age structures, including those of the Sevier fold and thrust belt, were reactivated during a period of Neogene extension (Snoke, 1993). Fault systems in or adjacent to the Southwestern and South-Central Wyoming study area include the Continental Fault system that borders the southwest Wind River Range and, farther east, the South Granite Mountains fault system (fig. 4). South of the Continental Fault system near Dickie Springs, paleoplacer gold occurrences thought to have been deposited during Neogene extension have been mined from White River Formation sandstone and conglomerate deposited in alluvial fans along the flanks of the southern Wind River Range. The paleoplacers are south of lode gold occurrences and are likely sourced by Archean greenstone rocks in the South Pass-Atlantic City mining district (Antweiler and others, 1980; Hausel and Love, 1991). Paleoplacers are discussed in detail and evaluated later in this report.

Neogene normal faulting in Wyoming appears to have occurred in a geographically transitional tectonic setting, as evidenced by the presence of non-extended terrain of the Great Plains (fig. 3) to the east, the highly extended Basin and Range physiographic province, and the northern extent of the Rio Grande Rift in central Colorado to the south (Snoke, 1993).

The Bear Lake Plateau block (fig. 2) of the Bear River Watershed study area is located on the northeast of the Basin and Range province (fig. 3). The Bear River valley, occupied by Bear Lake, is bounded by Neogene normal faults along the Bear River Range and Bear Lake Plateau (Reheis and others, 2009).

The Leucite Hills volcanic field is located partially within and adjacent to the Boars Tusk block of the Southwestern and South-Central Wyoming study area along the northeastern flank of the Rock Springs Uplift. The field is one of the youngest magmatic centers in Wyoming and is dated at 1.1 Ma (McDowell, 1971). Rock types consist of peralkaline (sodium+potassium>aluminum) ultrapotassic, mafic to ultramafic (very low silica) flows, dikes, necks, and plugs. These ultrapotassic rocks were investigated early in the 20th century as a potential source for potash fertilizer (Schulz and Cross, 1912). Pathfinder minerals for diamonds (pyrope garnet, chrome diopside, and orthopyroxene) have also been identified 64–80 km southwest of the Leucite Hills, although the source of the indicator minerals is uncertain (Hausel and others, 1995).

The Neogene was also characterized by voluminous, felsic caldera-forming eruptions of the Yellowstone volcanic field. Ash was deposited throughout the region for hundreds of kilometers from the caldera source areas. Ash units (Lava Creek B ash) are preserved in young sediments (fig. 6) in the Green River, Rock Springs, Great Divide, and Washakie Basin areas (Love and others, 1993). An active geothermal system, complex Holocene deformation history, and progression of young volcanism that occurred toward the northeast along the Yellowstone Hot Spot track are indicators of the potential for future active volcanism in this area (Girard and Stix, 2012).

The present topography of the study area—mountains that have high relief relative to surrounding sedimentary basins—has been strongly shaped by a late Cenozoic period of erosion. Large quantities of sediment were eroded from the basins during the Pliocene, when deep canyons were also cut into the southern Rocky Mountains (Scott, 1975). Erosion and glacial activity during this time sculpted mountains in Wyoming, eroded basin fill, and formed the present day landscape.

# Leasable Minerals

Leasable minerals include both fluid and solid minerals. Leasable fluid minerals include oil and gas and geothermal resources, and leasable solid minerals include coal, oil shale, native asphalt, phosphate, sodium salts such as halite and trona, potassium (potash), and sulfur (in Louisiana and New Mexico). Of these resources, because they are important in or immediately adjacent to the study area, oil and gas, geothermal, coal, phosphate, and potassium (potash) are discussed below. The world's largest deposit of trona, although important to the economy of Wyoming, is outside the study area and therefore is not discussed.

## Oil and Gas

The Southwestern and South-Central Wyoming and Bear River Watershed study areas lie within the Southwestern Wyoming and Wyoming Thrust Belt Oil and Gas Provinces (note that, although they have similar names, these provinces are not exactly the same areas as the Southwestern and South-Central Wyoming study area or the thrust belt). According to IHS ENERDEQ well data (IHS Energy Group, 2016), there has been no significant oil or gas production within the proposed withdrawal area within the study area (one inactive well in Sweetwater County, Wyoming, produced a minor amount of oil and gas). However, there has been oil and significant gas produced within some of the townships that contain the proposed withdrawal areas.

### Mineral Description

Petroleum is a naturally occurring mixture of gaseous, liquid, and solid hydrocarbons derived from the remains of plants and animals that lived millions of years ago. The USGS National Oil and Gas Assessment (NOGA) team assesses the potential undiscovered petroleum (oil, natural gas, and natural gas liquids (NGLs), such as propane and butane) resources throughout the country. The results of these assessments are discussed in more detail within the published reports referred to in this report.

### Geology and Occurrence

The total petroleum system (TPS) concept is used by the USGS to assess the potential petroleum resources within an area. As defined by Magoon and Schmoker (2000), the TPS has

> . . . the essential elements (source rock, reservoir rock, seal rock, and overburden rock) and processes (generation-migration-accumulation and trap formation) as well as all genetically related petroleum that occurs in seeps, shows, and accumulations, both discovered and undiscovered, whose provenance is a pod or closely related pods of active source rock. The TPS is a naturally occurring hydrocarbon-fluid system in the lithosphere that can be mapped, and includes the essential elements and processes needed for oil and gas accumulations to exist. The TPS concept presumes that migration pathways must exist, either now or in the past, connecting the provenance with the accumulations. . . The goal, then, is to map this natural fluid system, or TPS, in three dimensional space through time to locate, define, and evaluate those areas for undiscovered hydrocarbons.

Within the Southwestern Wyoming Province there are nine TPSs defined, and in the Wyoming Thrust Belt Province there are two TPSs defined.

Within the Southwestern and South-Central Wyoming and Bear River Watershed study area, there are conventional and unconventional (continuous) resources (fig. 7). The hydrocarbon source rocks in the area are Eocene to Permian in age and include the Wasatch, Green River, Lance, and Fort Union Formations; Mesaverde Group; Lewis Shale; Niobrara Formation; the Hilliard, Baxter, and Mowry Shales; and the Phosphoria Formation (fig. 8). The reservoir rocks in the area include the Frontier, Morrison, and Sundance Formations; the Dakota, Muddy, Nugget, and Tensleep Sandstones; and the Madison Limestone. Conventional oil and gas have been produced from both stratigraphic and structural traps.

### Exploration and Development

Of the 72 townships containing proposed withdrawal areas in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, only five are not associated with an oil and gas assessment unit (appendix 4). Although there are many assessed potential oil and gas resources in the area and near the study area, there has not been any significant hydrocarbon production within the study area, and the overall potential appears to be low to moderate, considering the presence of several dry wells within the study area.

### Production

As previously mentioned, one well, now inactive, in Sweetwater County, Wyoming, produced a minor amount of oil and gas within the proposed withdrawal area (IHS Energy Group, 2016). Oil and gas has been produced within the townships surrounding some of the study areas. As table 4 shows, there have been almost 2.4 million barrels of oil (MMBO) and

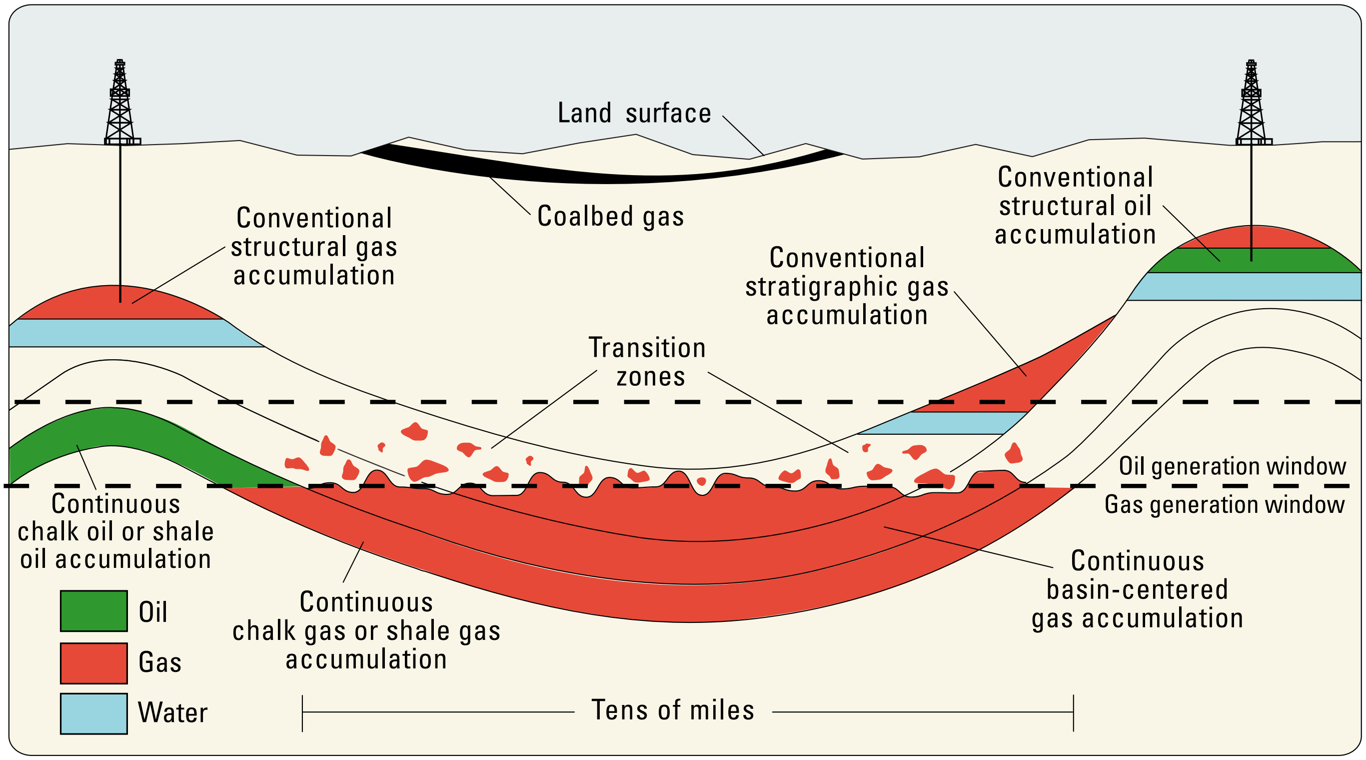



**Figure 7.** Illustration showing categories of oil and natural-gas accumulations (after U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005b).

**Table 4.** Cumulative oil and gas production per township in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah (Gunther and others, 2016b).

[PLSSID, Public Land Survey System Identifier, a concatenation of the state, principal meridian, township, range, and duplicate code; MCF, thousand cubic feet; WYO, Southwestern and South-Central Wyoming; Bear River Watershed, Bear River Watershed. See figure 17 for location of townships with these PLSSIDs]

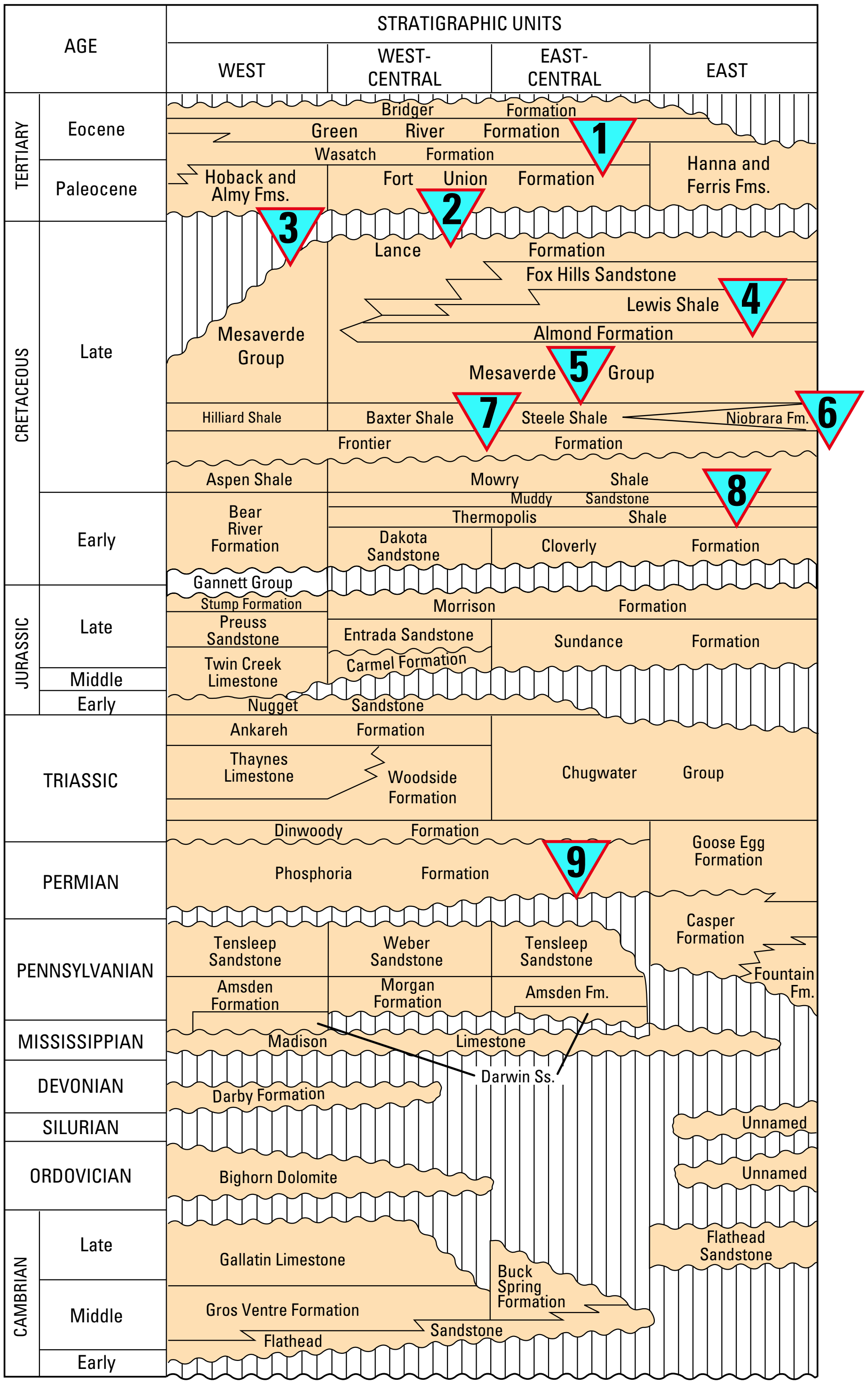
| PLSSID | Study area | Cumulative liquid (barrels) | Cumulative gas (MCF) |
|---|---|---|---|
| WY060260N1070W0 | WYO | 581 | 582 |
| WY060270N1070W0 | WYO | 4,171 | 29,191 |
| WY060270N1080W0 | WYO | 4,431 | 466,026 |
| WY060240N1140W0 | BRW | 4,595 | 11,068,643 |
| WY060220N1040W0 | WYO | 11,556 | 421,780 |
| WY060230N1150W0 | BRW | 12,168 | 2,364,158 |
| WY060220N1150W0 | BRW | 20,226 | 1,942,695 |
| WY060270N1060W0 | WYO | 24,031 | 570,037 |
| WY060230N1130W0 | BRW | 200,012 | 12,122,880 |
| WY060240N1120W0 | BRW | 301,983 | 799,513 |
| WY060220N1130W0 | BRW | 737,378 | 36,012,018 |
| WY060210N1180W0 | BRW | 1,070,774 | 5,222,511 |
| Total | | 2,391,906 | 71,020,034 |

more than 71 billion cubic feet (BCF) of gas produced in the townships containing the study areas.

## Results of Previous USGS Assessments

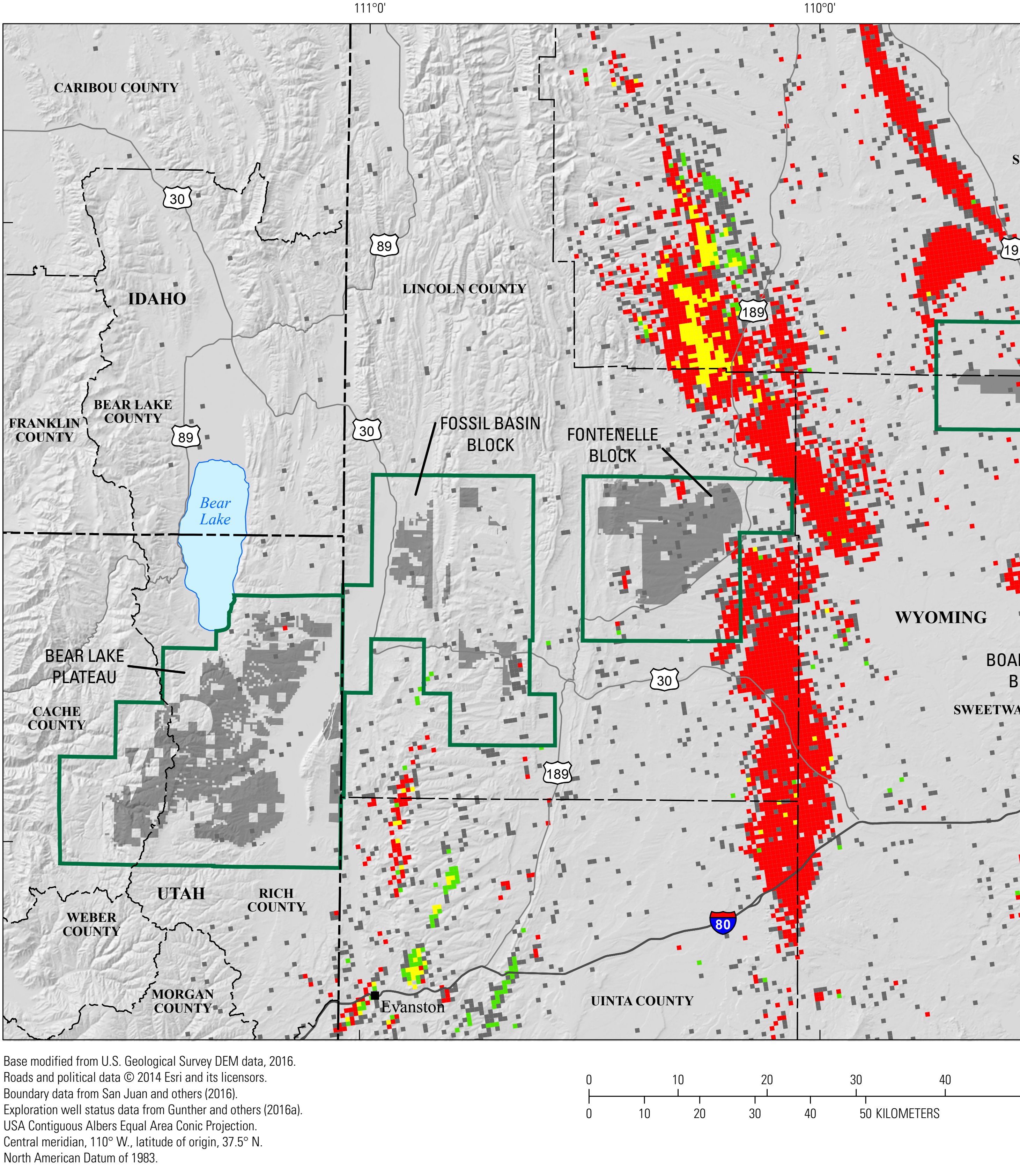
This area has been extensively assessed for potential hydrocarbon resources (figs. 9, 10, 11). Within the USGS Southwestern Wyoming and Wyoming Thrust Belt Oil and Gas Provinces (fig. 12), there are 35 assessed units (U.S. Geological Survey, 2004, 2005a). Of these, the 15 prior to 1995 are termed ‘plays’ (Law, 1995); the 20 after 1995 are referred to as ‘assessment units.’ (Appendix 4 lists oil and gas plays and assessment units the Southwestern and South-Central Wyoming and Bear River Watershed study areas.)

Within the Wyoming Thrust Belt Province, there are assessed mean potential resources (table 5) of almost 39 million barrels of oil (MMBO), 556.92 billion cubic feet of gas (BCFG) and 57.27 million barrels natural gas liquids (MMBNGL), as well as mean potential coalbed gas resources of 361 BCFG (U.S. Geological Survey, 2004). Within the Southwestern Wyoming Province, the USGS has assessed potential mean resources of 131 MMBO, 84,590 BCFG, and 2,578 MMBNGL (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2002). For more details about the geologic oil and gas assessment of this area, please see the aforementioned USGS oil and gas assessment reports and U.S. Geological Survey Southwestern Wyoming Province Assessment Team (2005a).




1. Wasatch–Green River Composite TPS
2. Lance–Fort Union Composite TPS
3. Mesaverde–Lance–Fort Union Composite TPS
4. Lewis TPS
5. Mesaverde TPS
6. Niobrara TPS
7. Hilliard–Baxter-Mancos TPS
8. Mowry Composite TPS
9. Phosphoria TPS

**Figure 8.** Generalized stratigraphic column of Southwestern Wyoming Province with numbered total petroleum systems (TPSs) (from U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005b). Fm., Formation; Ss., Sandstone.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LINCOLN COUNTY
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BLOCK
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WYOMING
BEAR LAKE
PLATEAU
CACHE
COUNTY
UTAH
RICH
COUNTY
WEBER
COUNTY
MORGAN
COUNTY
Evanston
UINTA COUNTY
30
89
189
80
Base modified from U.S. Geological Survey DEM data, 2016.
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Boundary data from San Juan and others (2016).
Exploration well status data from Gunther and others (2016a).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.
0 10 20 30 40
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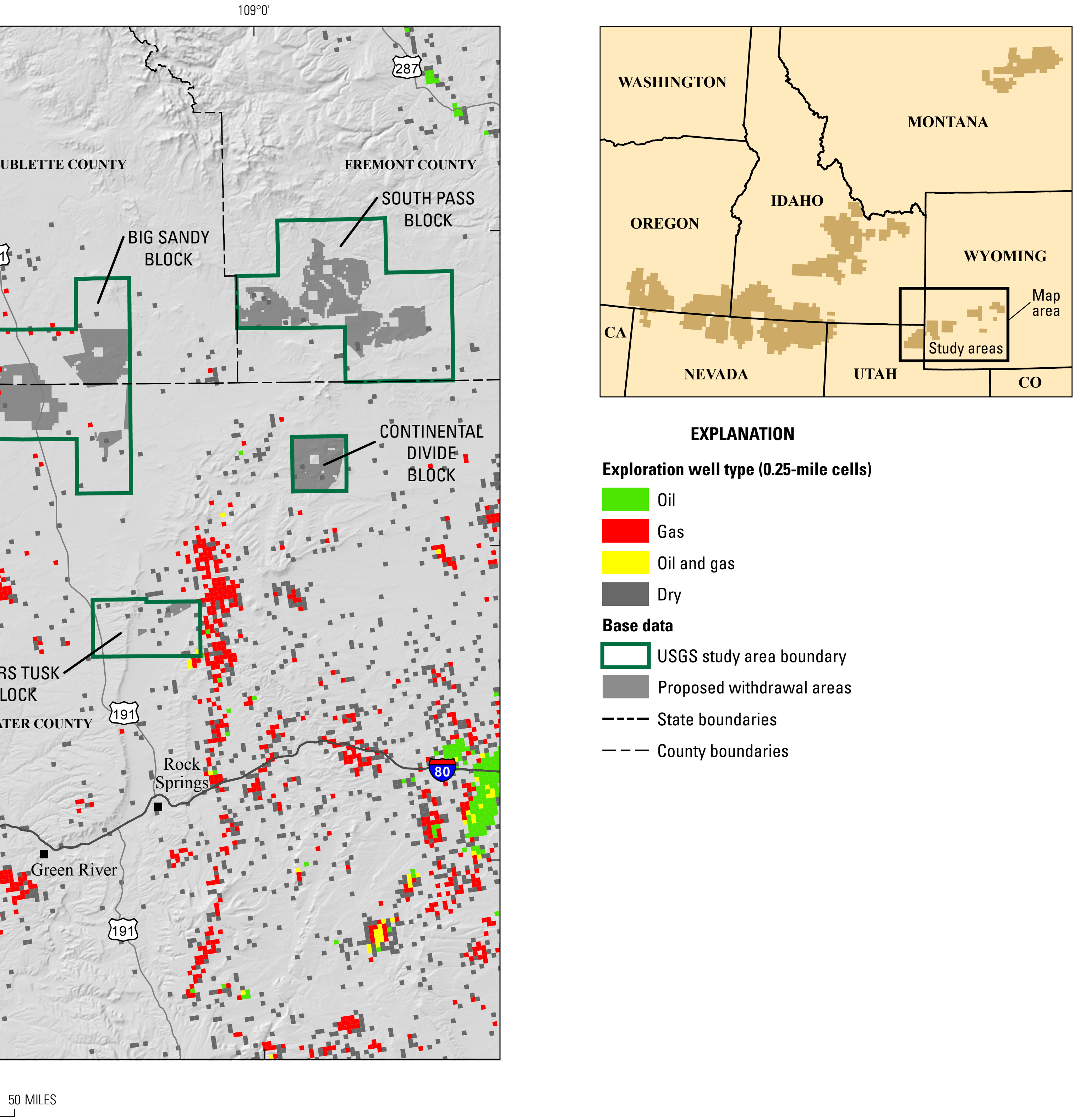
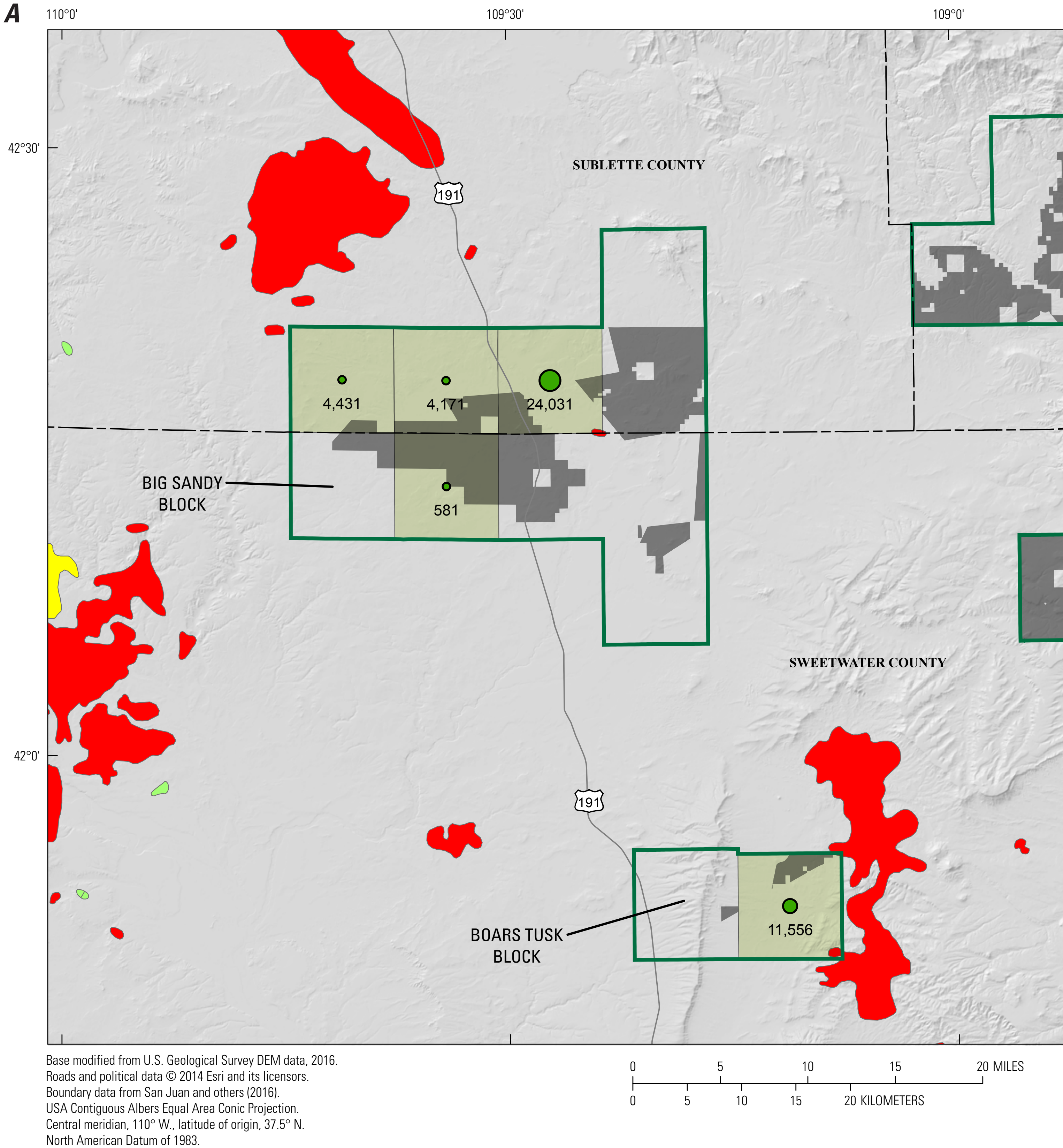



**Figure 9.** Map showing well type by quarter cell (0.25 mile) summary of exploration and well type (Gunther and others, 2016a) in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.

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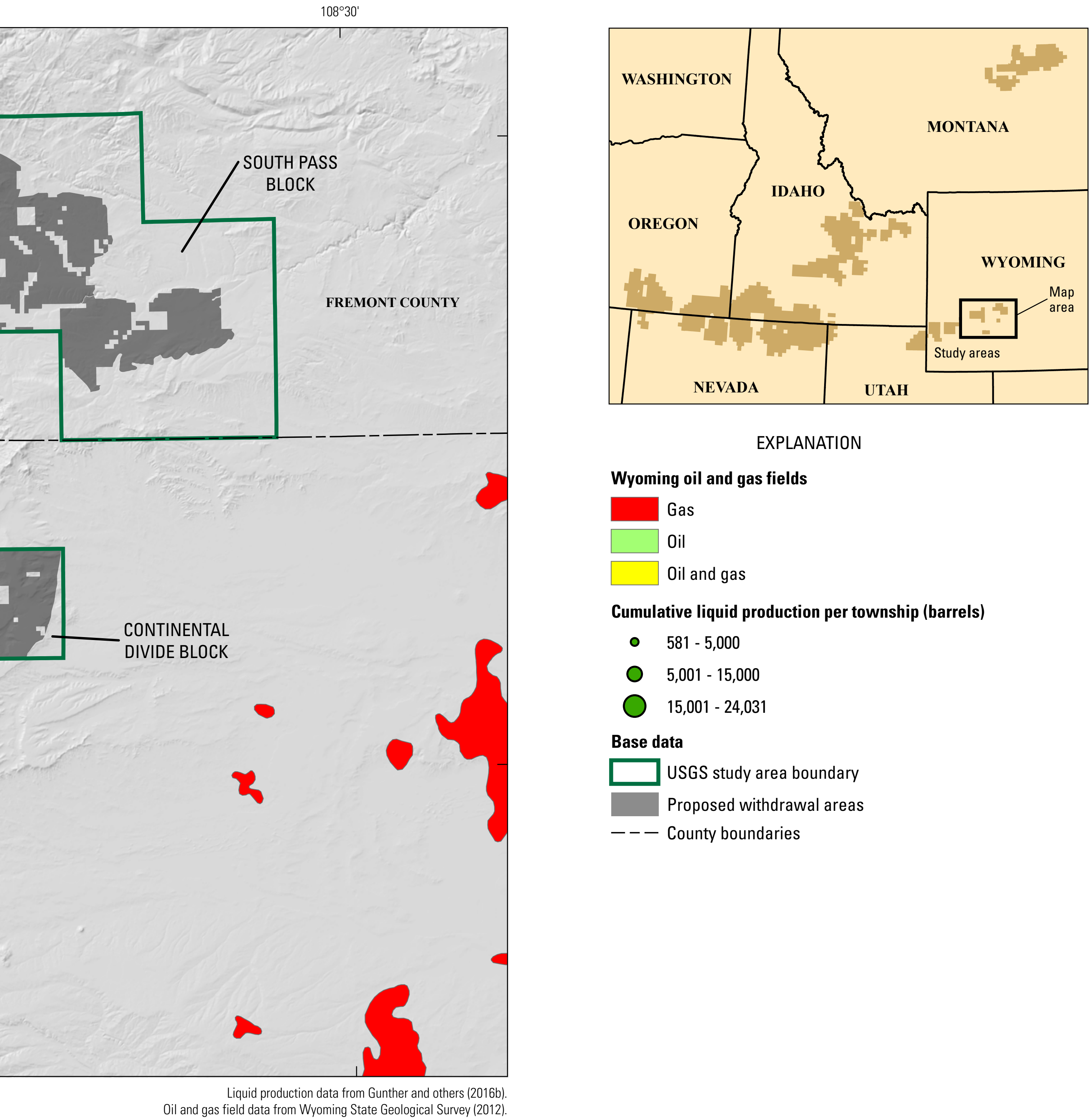
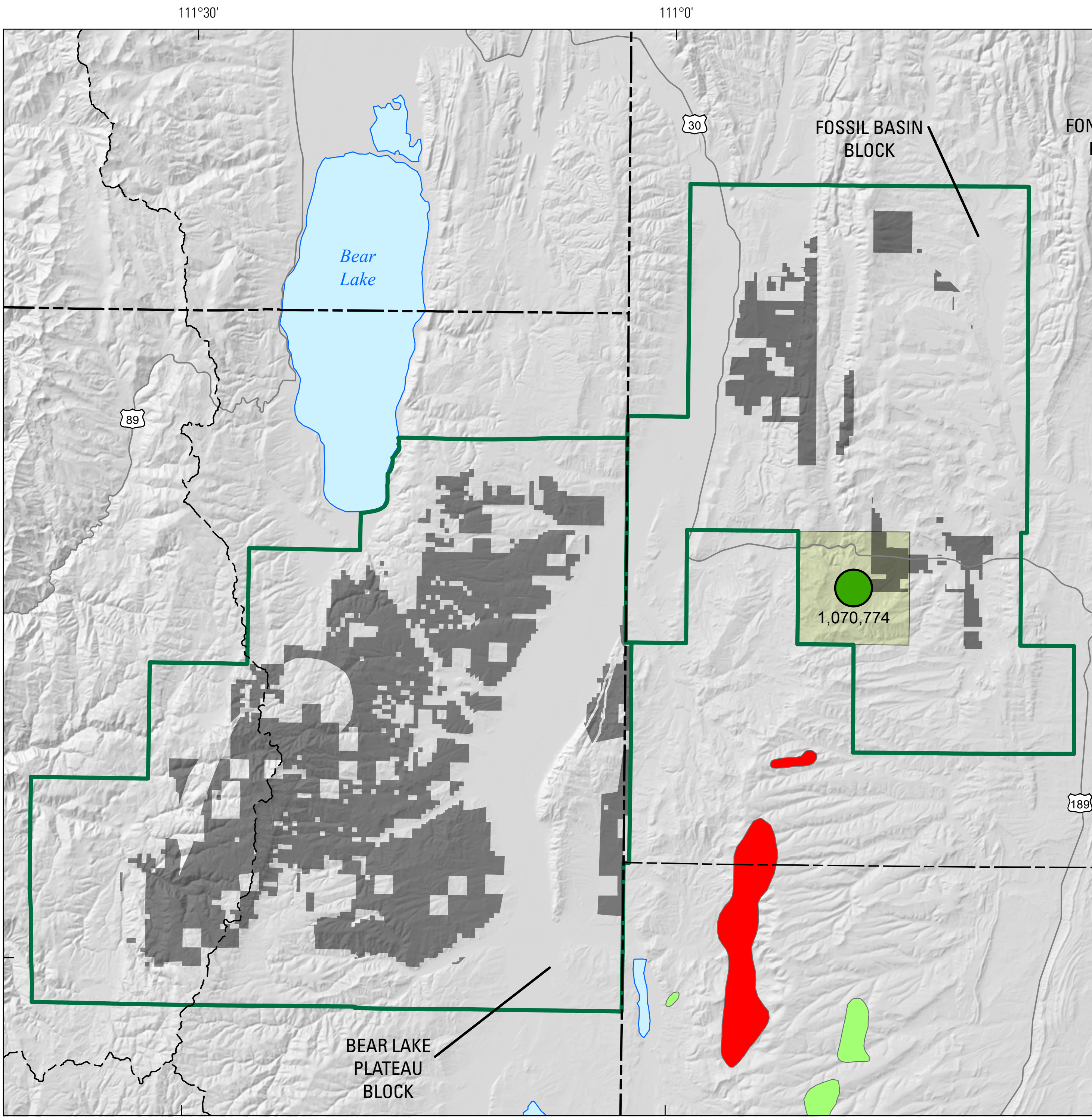



**Figure 10.** Maps showing cumulative liquid (oil) production from Wyoming oil and gas fields by township (Gunther and others, 2016b) in the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah. USGS, U.S. Geological Survey.

***B***

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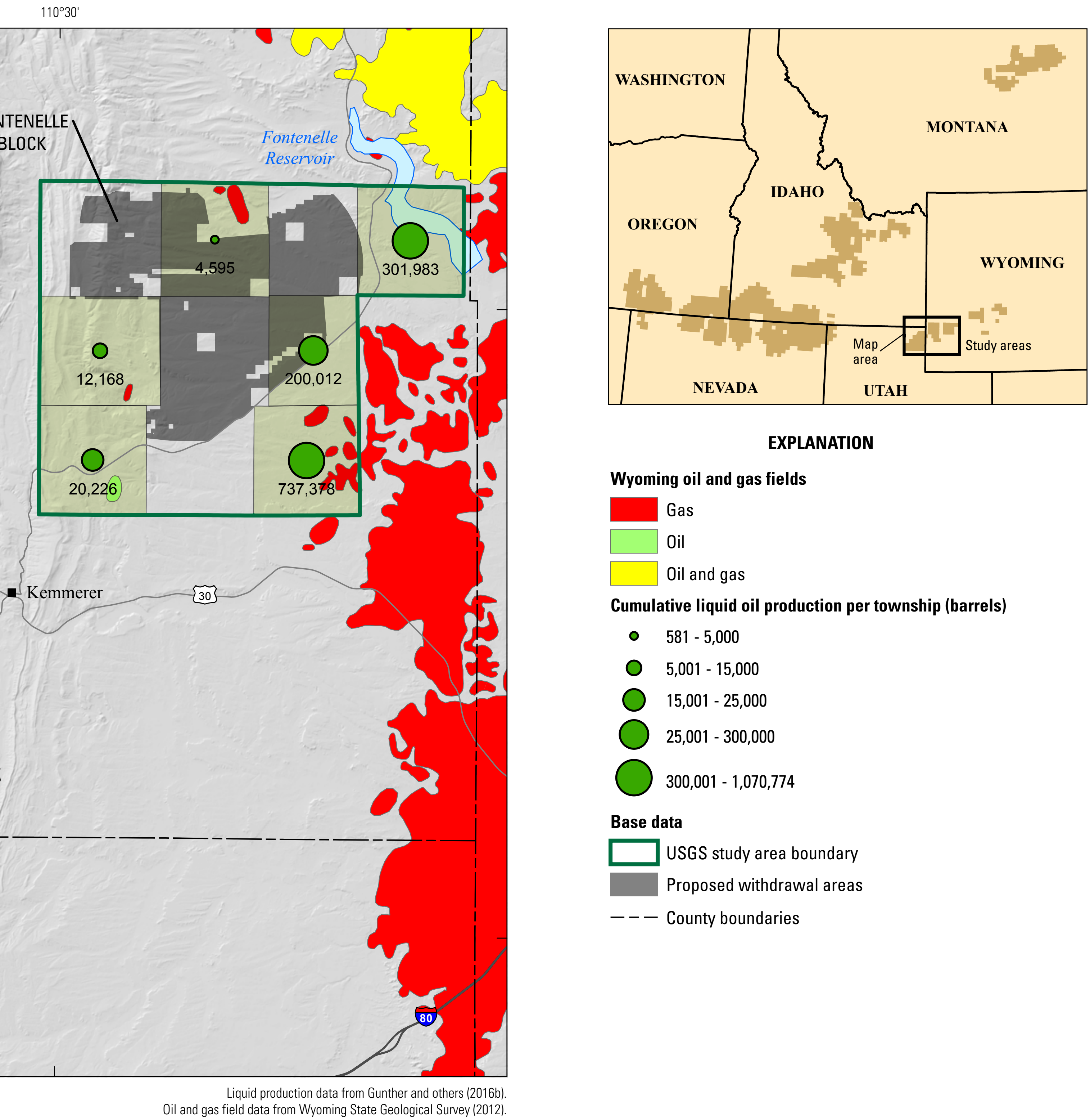
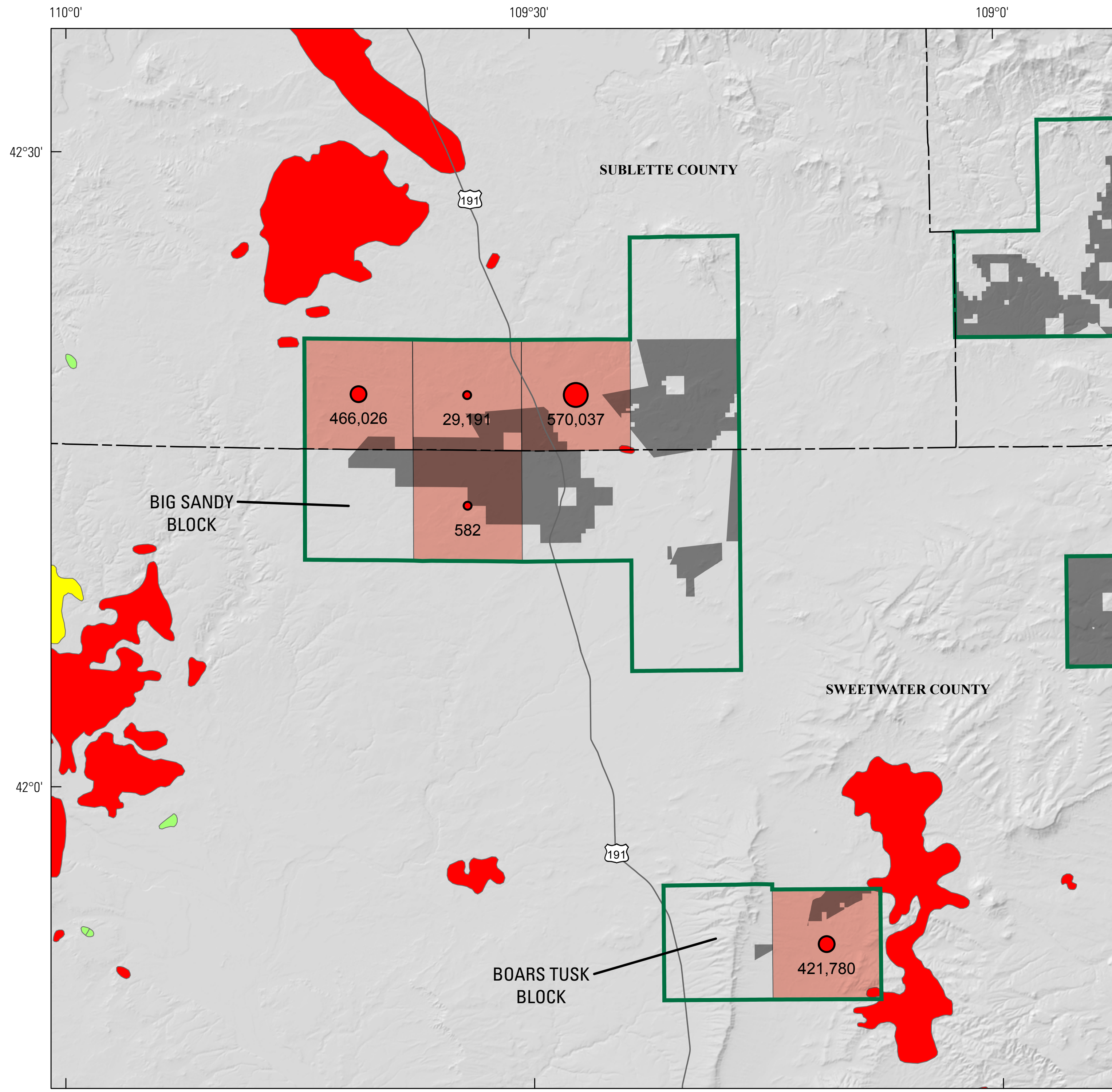



**Figure 10.**—Continued

*A*

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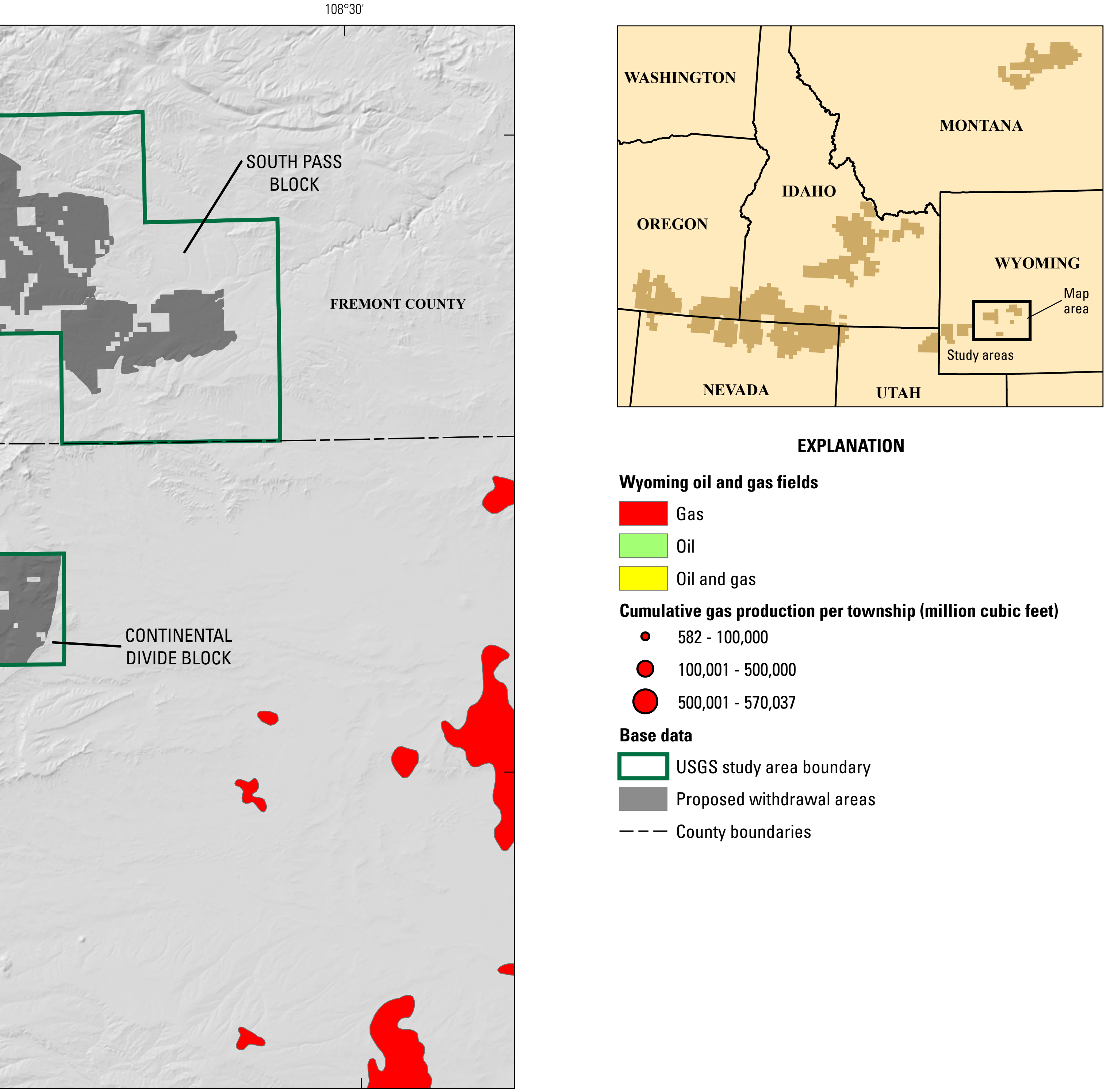
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

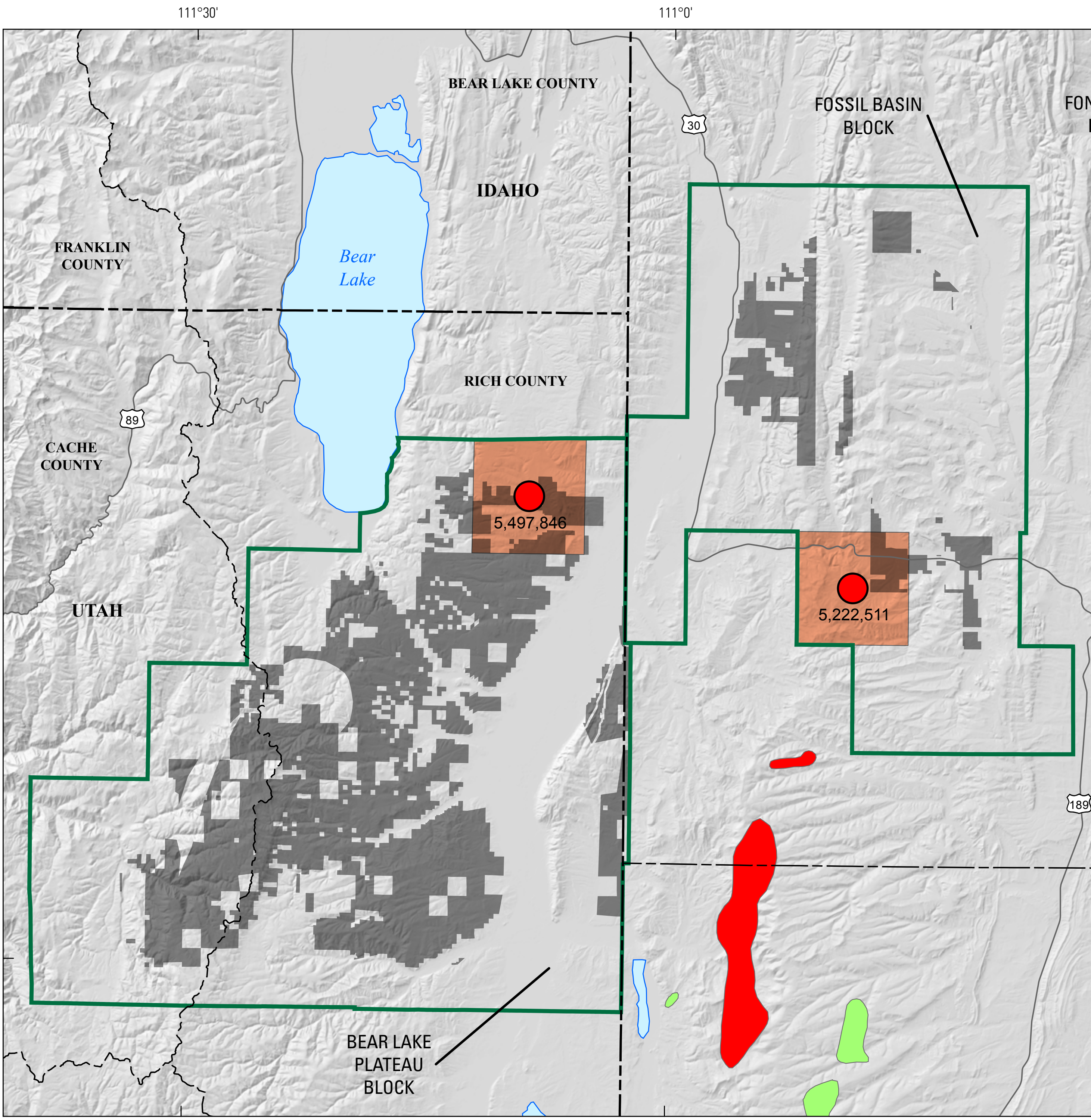
0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS




Production data from Gunther and others (2016b).
Oil and gas field data from Wyoming State Geological Survey (2012).

**Figure 11.** Maps showing cumulative gas production from Wyoming oil and gas fields by township (Gunther and others, 2016b) in the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah. USGS, U.S. Geological Survey.

***B***

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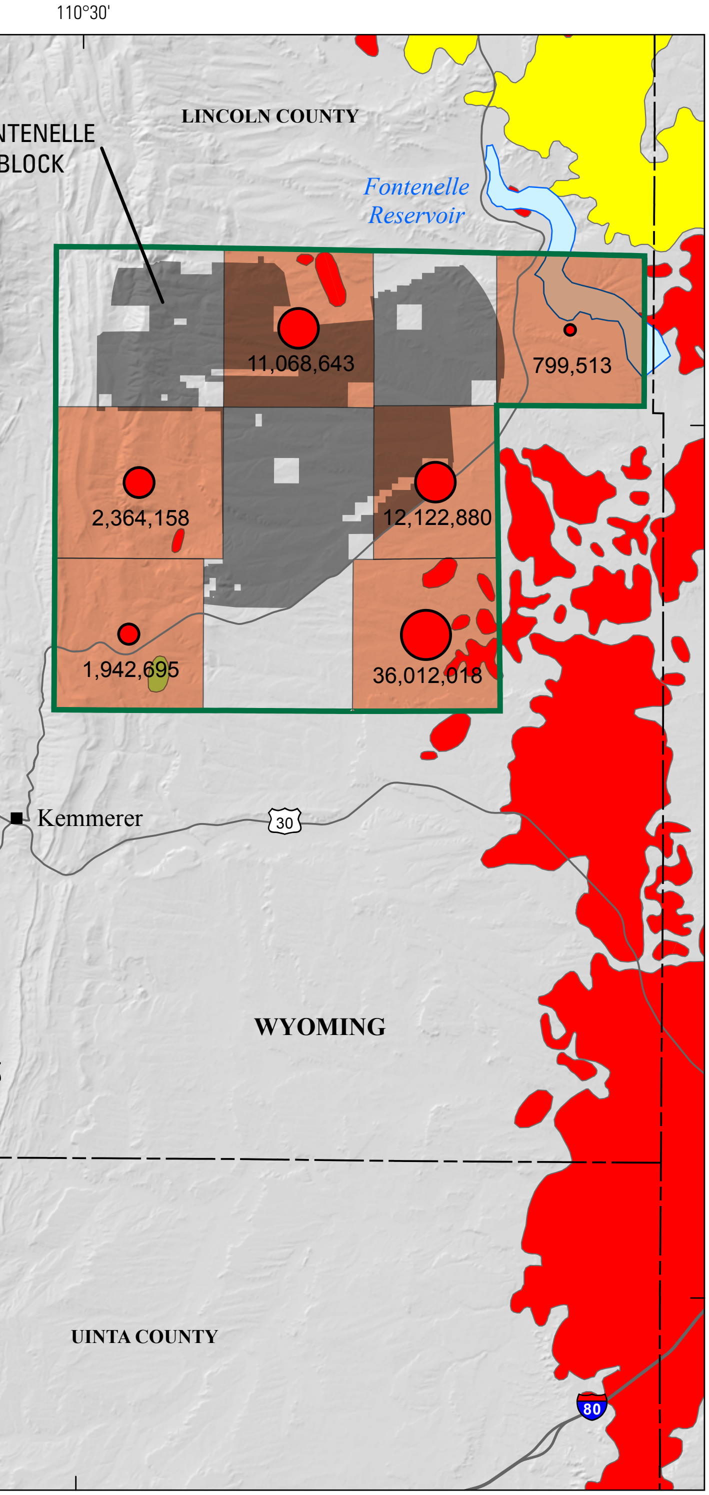
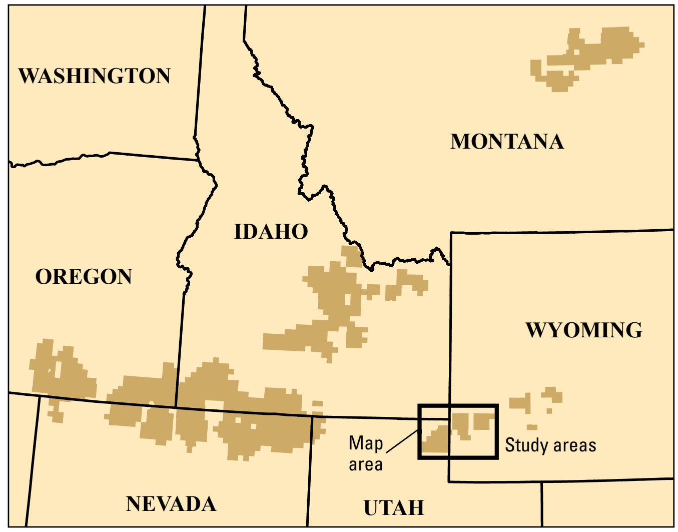
North American Datum of 1983.

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS




Production data from Gunther and others (2016b).
Oil and gas field data from Wyoming State Geological Survey (2012).




**EXPLANATION**

**Wyoming oil and gas fields**

Gas

Oil

Oil and gas

**Cumulative gas production per township (million cubic feet)**

582 - 800,000

800,001 - 2,000,000

2,000,001 - 5,000,000

5,000,001 - 13,000,000

13,000,001 - 36,012,018

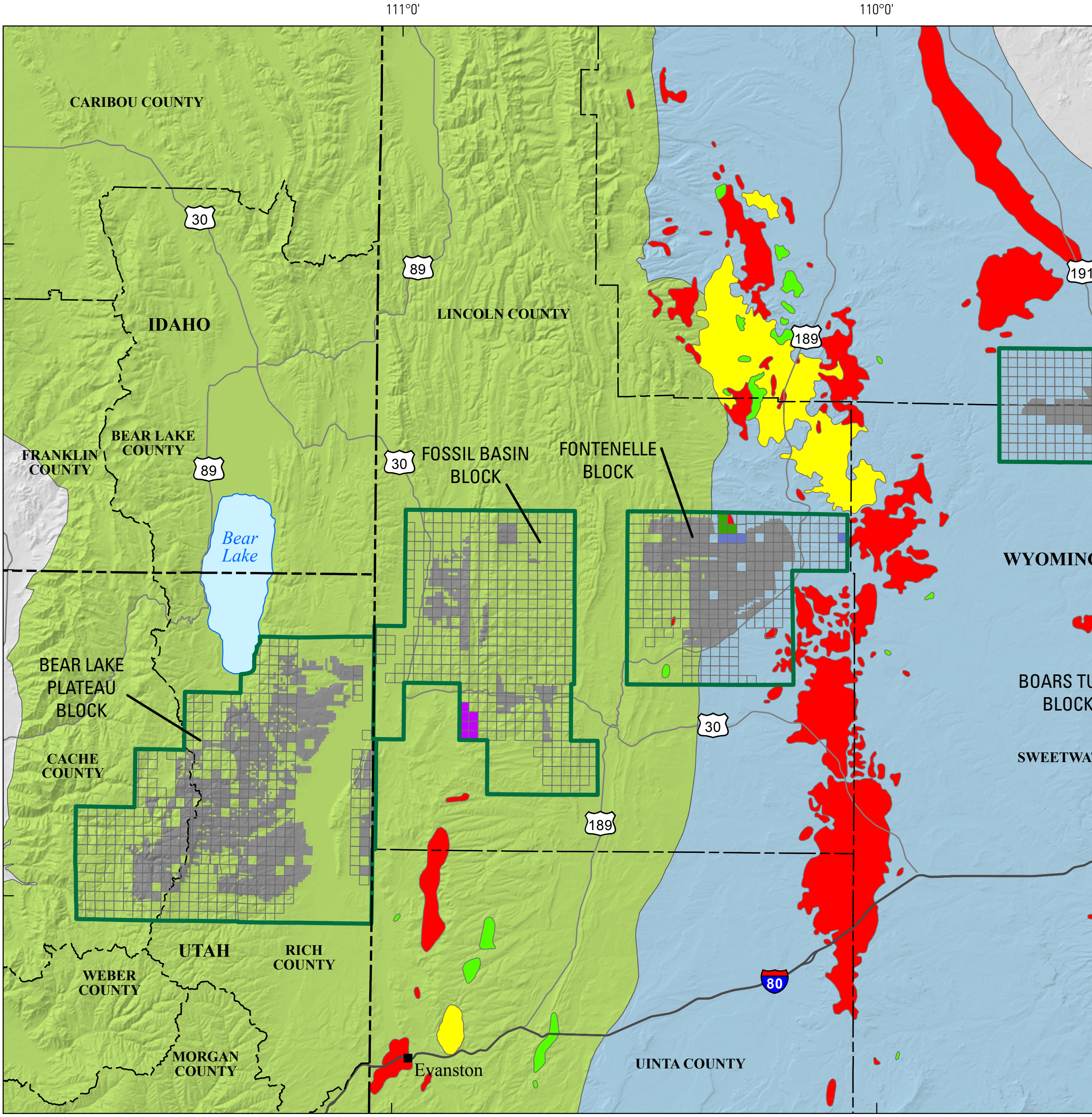
**Base data**

USGS study area boundary

Proposed withdrawal areas

County boundaries

**Figure 11.**—Continued

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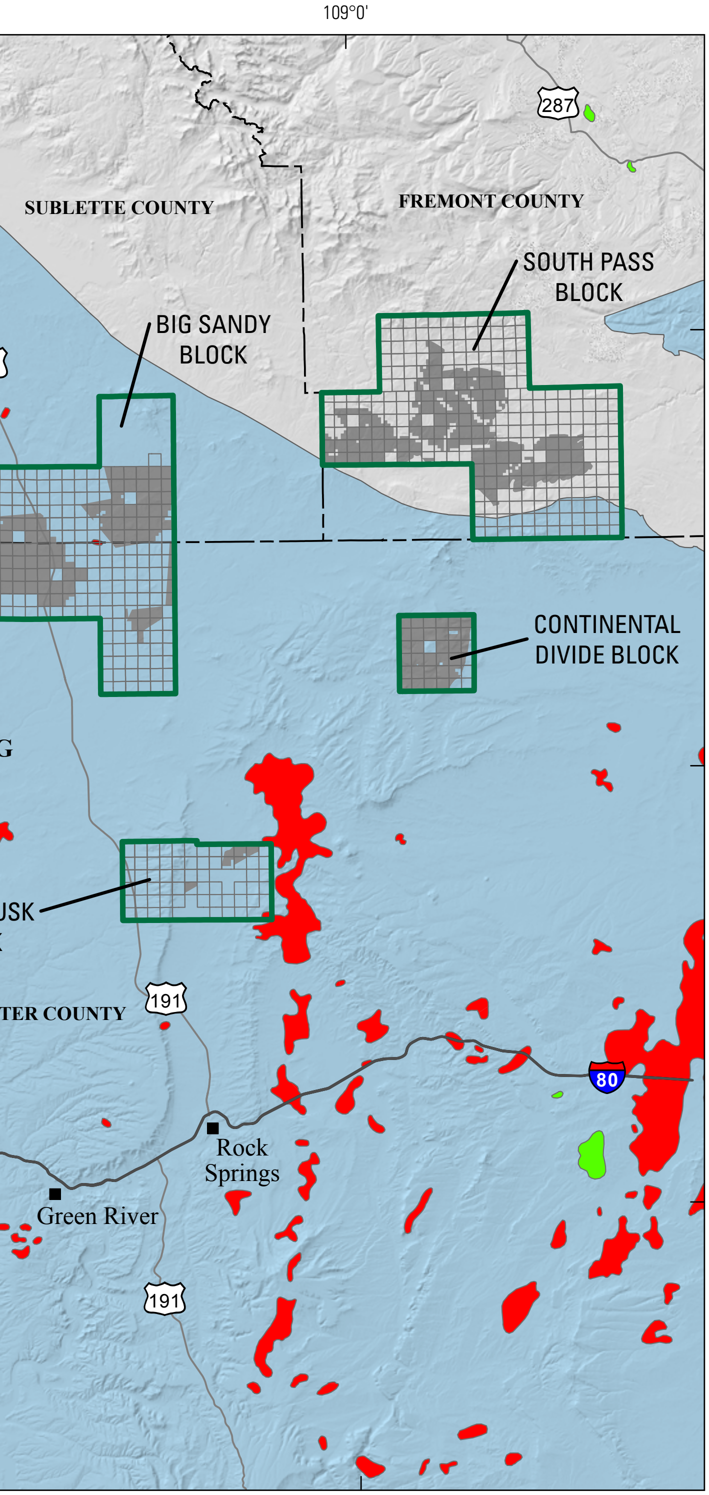
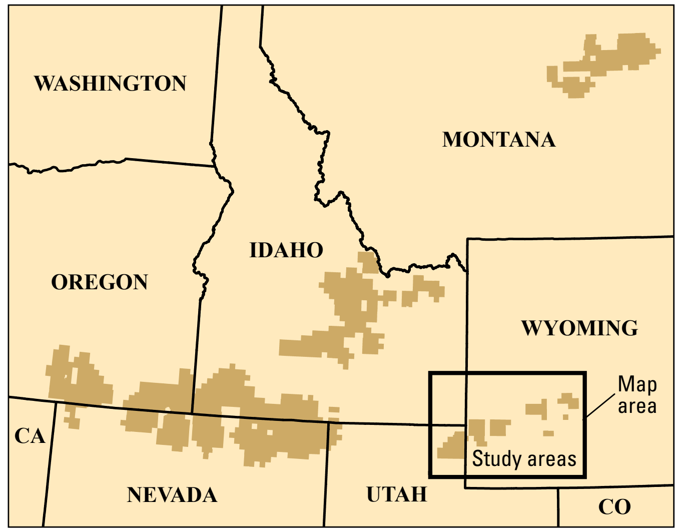
North American Datum of 1983.

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS




Oil and gas provinces from USGS SW WY Oil and Gas Assessment Team (2005a).
Oil and gas field data from Wyoming State Geological Survey (2012).
Dicken and San Juan (2016).




**EXPLANATION**

**Oil and gas leases by section**

Authorized competetive oil and gas lease on public land

Authorized noncompetetive oil and gas lease on public land

Authorized simultaneous oil and gas lease on public land

Closed lease

**Oil and gas field type**

Oil

Gas

Oil and gas

**Oil and gas provinces**

Wyoming Thrust Belt oil and gas province

Southwestern Wyoming oil and gas province

**Base data**

USGS study area boundary

Proposed withdrawal areas

State boundaries

County boundaries

**Figure 12.** Map showing Federal oil and gas leases and oil and gas provinces within the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.

**Table 5.** Assessed oil and gas potential in the Wyoming Thrust Belt and Southwestern Wyoming Provinces (U.S. Geological Survey, 2004; U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005a).

[AU, assessment unit; MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels natural gas liquids]

| Resource type | Mean oil (MMBO) | Mean gas (BCFG) | Mean natural gas liquids (MMBNGL) |
|---|---|---|---|
| Wyoming Thrust Belt Province | | | |
| Conventional | | | |
| Thrust Belt Conventional AU | 38.83 | 556.92 | 57.27 |
| Coalbed gas | | | |
| Frontier-Adaville-Evanston Coalbed Gas AU | | 361.1 | 0 |
| Southwestern Wyoming Province | | | |
| Conventional | 27.83 | 2,420.8 | 73.93 |
| Coalbed gas | 0 | 1,528.92 | 0 |
| Tight gas | 0 | 80,577.67 | 2,500.28 |
| Conventional oil | 103.64 | 62.18 | 3.73 |

## Geothermal Energy

Geothermal energy constitutes one of the Nation's largest sources of renewable electric power. Its potential is an important consideration, given that current projections indicate the United States will need to increase its electrical power generating capacity by approximately 25 percent over the next 25 years (Energy Information Administration, 2015). Although the installed capacity of geothermal (approximately 3,000 megawatts electric, MWe) falls short of meeting the Nation's power needs, it constitutes a fraction of the estimated available resources based on recent assessments. With potential advances in exploration and development technologies, geothermal resources could provide a significant source of baseload electric power. Because of government mandates and incentives for renewable energy, it is expected that the demand for geothermal energy will continue to grow, and, given the concentration of geothermal resources in the Western United States, a significant part of this growth could occur on public lands. This section, which provides a review of the geothermal resource potential of the study areas, is based on the results of the USGS 2008 assessment of the Nation's moderate- and high-temperature geothermal resources (Williams and others, 2008) that includes a provisional assessment for enhanced geothermal systems (EGS), as well as earlier USGS and state-level inventories and assessments.

### Mineral Description

Geothermal resources can be divided into two categories—conventional and unconventional. Conventional resources are those geothermal systems defined by Muffler (1979) as "any regionally localized geological setting where naturally occurring parts of the Earth's thermal energy are transported close enough to the Earth's surface by circulating steam or hot water to be readily harnessed for use." These geothermal (or alternatively, hydrothermal) systems involve the natural vertical movement of water through either free or forced convection (for example, Duffield and Sass, 2003). All of the geothermal systems developed for commercial electric power generation in the United States fall in this category. Within this framework, identified hydrothermal systems are divided into three temperature classes: low-temperature (<90 degrees Celsius, °C), moderate-temperature (90 to 150 °C), and high-temperature (>150 °C). High-temperature systems include both liquid- and vapor-dominated resources. Moderate-temperature systems are almost exclusively liquid-dominated, and all low-temperature systems are liquid-dominated. All three temperature classes are suitable for direct use applications, but in general, only moderate- and high-temperature systems are viable for electric power generation. The heat source of a hydrothermal system can be characterized as either magmatic or amagmatic. Magmatic geothermal reservoirs, which derive their heat from shallow-crustal magma bodies, are typically larger and higher in temperature than amagmatic systems, which owe their heat to deep circulating fluids within the background geothermal gradient of the upper crust (Coolbaugh and others, 2006).

Unconventional geothermal resources may have the technical potential for electric power generation, reductions in demand for other nonrenewable sources of energy, or direct-use applications, but have not yet been adopted on a commercial basis. These resources include deep, high-temperature sedimentary basins, especially geothermal resources collocated with oil and gas accumulations or zones of geopressured fluids, and enhanced geothermal systems (EGS). EGS constitute the part of a geothermal resource for which a measureable increase in production over its natural state is or can be attained through mechanical, thermal, and (or) chemical stimulation of the reservoir rock (Williams and DeAngelo, 2011).

## Geology and Occurrence

Compilations of geothermal occurrences in Wyoming and Utah (Breckenridge and Hinckley, 1978; Reed and others, 1983; Lienau and Ross, 1996; Blackett and Wakefield, 2004) do not identify any thermal springs or wells within the boundaries of the Southwestern and South-Central Wyoming and Bear River Watershed study areas (fig. 13). This absence of geothermal manifestations is consistent with the relatively low values of favorability for the occurrence of moderate- and high-temperature geothermal systems across the region spanned by the study areas, with the exception of the part of the Bear River Watershed study area that extends into eastern Cache County in Utah (fig. 14). This low favorability reflects the relative absence of factors associated with the formation of moderate- and high-temperature geothermal systems, such as seismicity, Quaternary faulting, Quaternary magmatic activity, a dominantly extensional crustal stress regime, or high crustal heat flow (Williams and DeAngelo, 2008).

Low-temperature thermal springs and wells outside of the study areas in Wyoming, southeastern Idaho, and northeastern Utah (figs. 13 and 14) occur in diverse settings. Those in the thrust belt to the west and northwest of the Bear River Watershed study area are the result of fluid circulation in permeable faults and fractures driven by differences in topography. Those to the north and northeast in Sublette and Fremont Counties of Wyoming correlate with shallow thermal aquifers formed due to flow along permeability contrasts in sedimentary units (Breckenridge and Hinckley, 1978). Low-temperature resources can be exploited for direct-use applications (for example, greenhouses, aquaculture, district heating, drying for industrial and agricultural applications), provided the infrastructure for those applications is located on site.

## Exploration and Development

### Southwestern and South-Central Wyoming Sagebrush Study Area

Exploration for hydrothermal systems within and near the Southwestern and South-Central Wyoming study area has been limited to four crustal heat flow measurements (Williams and DeAngelo, 2011). These range from an average of approximately 50 milliwatts per square meter (mW $m^{-2}$) at the southwestern boundary of the Wind River Range to approximately 70 mW $m^{-2}$ south of the study area within the greater Green River Basin. The values of heat flow near the Wind River Mountains are elevated in comparison with other Archean terranes, most likely because of thinning of the lithosphere during the Laramide orogeny (Lenardic, 1997), but are still relatively low in comparison to the average crustal heat flow in the Western United States.

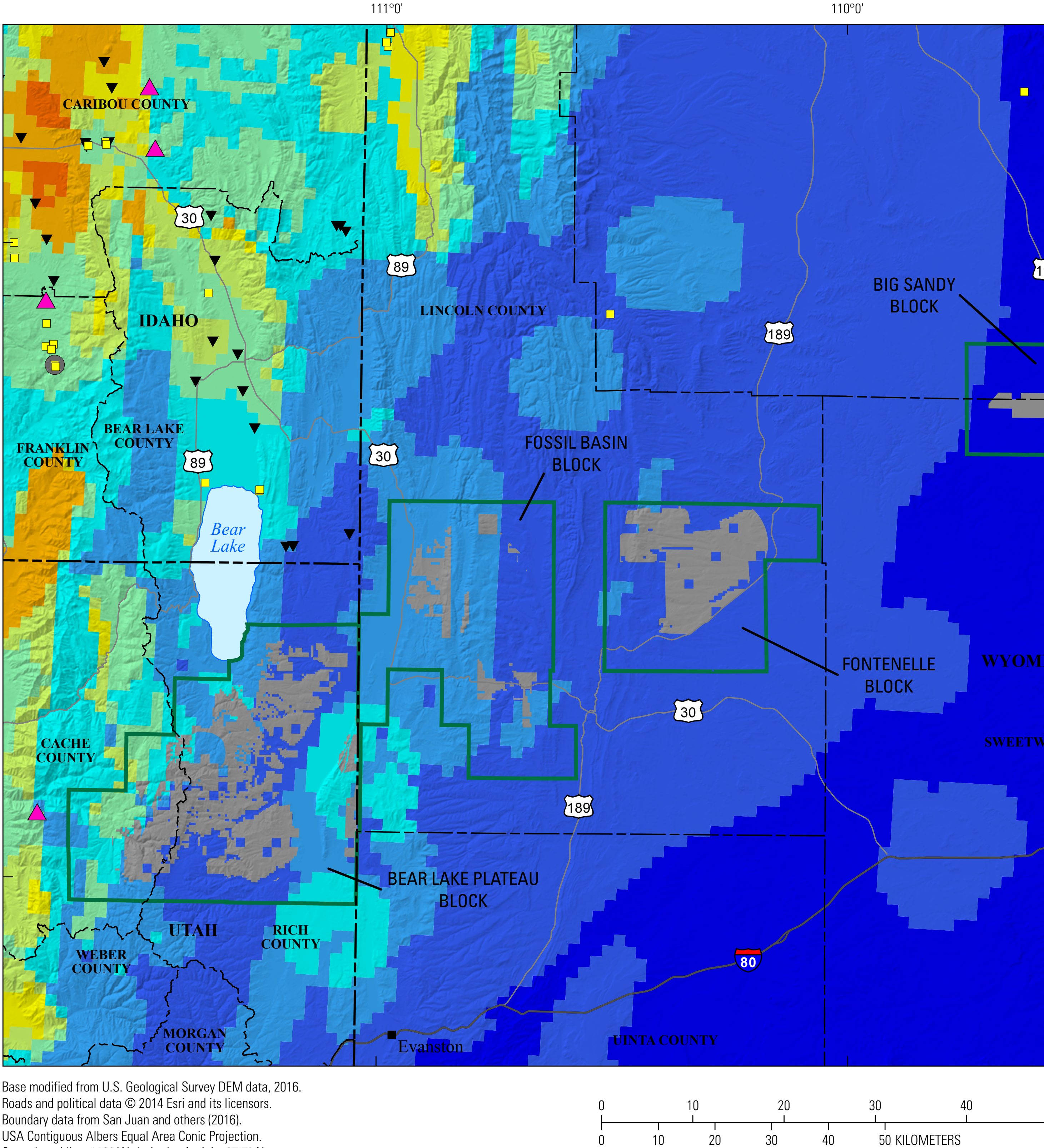
Higher heat flow in the greater Green River Basin, although not indicative of favorability for the occurrence of moderate- and high-temperature hydrothermal systems due to the absence of other contributing factors such as seismicity, Quaternary faulting, Quaternary magmatic activity, or a dominantly extensional crustal stress regime, is consistent with conductive geothermal resources in the deeper permeable units of the basin. Temperature gradient mapping based on the bottom hole temperature (BHT) records from oil and gas exploration wells indicates that formations in the Green River Basin can reach or exceed temperatures of 93 °C (200 Fahrenheit, °F) at depth (Finn, 2002). Although the lowest temperature commercial geothermal development in the conterminous United States is a 107 °C resource at Wabuska, California, a recent Department of Energy-funded project at the Rocky Mountain Oilfield Testing Center in the Powder River Basin demonstrated the technical capability of generating electric power from produced oil field waters with in situ temperatures that range from 90 to 95 °C (Anderson, 2010).

### Bear River Watershed Study Area

As noted above, the Bear River Watershed study area extends from the greater Green River Basin westward across the Wyoming thrust belt to the eastern edge of the Great Basin, from a region of relatively low hydrothermal favorability in the eastern part of the study area (fig. 13) to a region of higher favorability in the west. Higher heat flow, as well as seismicity and Quaternary faulting, are indications of crustal permeability (Williams and Deangelo, 2008). As a result, the western reaches of the study area carry the highest potential for this region, even though there are no identified low or moderate-to-high-temperature geothermal systems within the Bear River Watershed study area. There is a geothermal development site located just west of the Bear Lake Plateau block (fig. 2) in Cache County, Utah—the Renaissance geothermal prospect (Austin and others, 2006). This prospect may be related to a permeable fault zone that was penetrated by a petroleum exploration well at a depth of 2,500 m in 1974 and which yielded hot water at a temperature of approximately 140 °C.

## Results of Previous USGS Assessments

The 2008 USGS geothermal resource assessment (Williams and others, 2008) did not identify any moderate- or high-temperature geothermal systems within the Utah-Wyoming study areas. The assessment of undiscovered resources was based, in part, on a series of geographic information systems (GIS) logistic regression analyses through which geothermal potential was modeled using a weighted combination of evidence layers derived from mappable geologic and tectonic features available in digital databases (Williams and DeAngelo, 2008; Williams and others, 2009). Figure 13 illustrates the distribution of relative geothermal potential from these analyses across the region encompassing the Southwestern and South-Central Wyoming and Bear River Watershed study areas. Mean favorability for conventional resources in the Bear River Watershed is approximately 50 percent of the average for the entire Western United States, whereas that for

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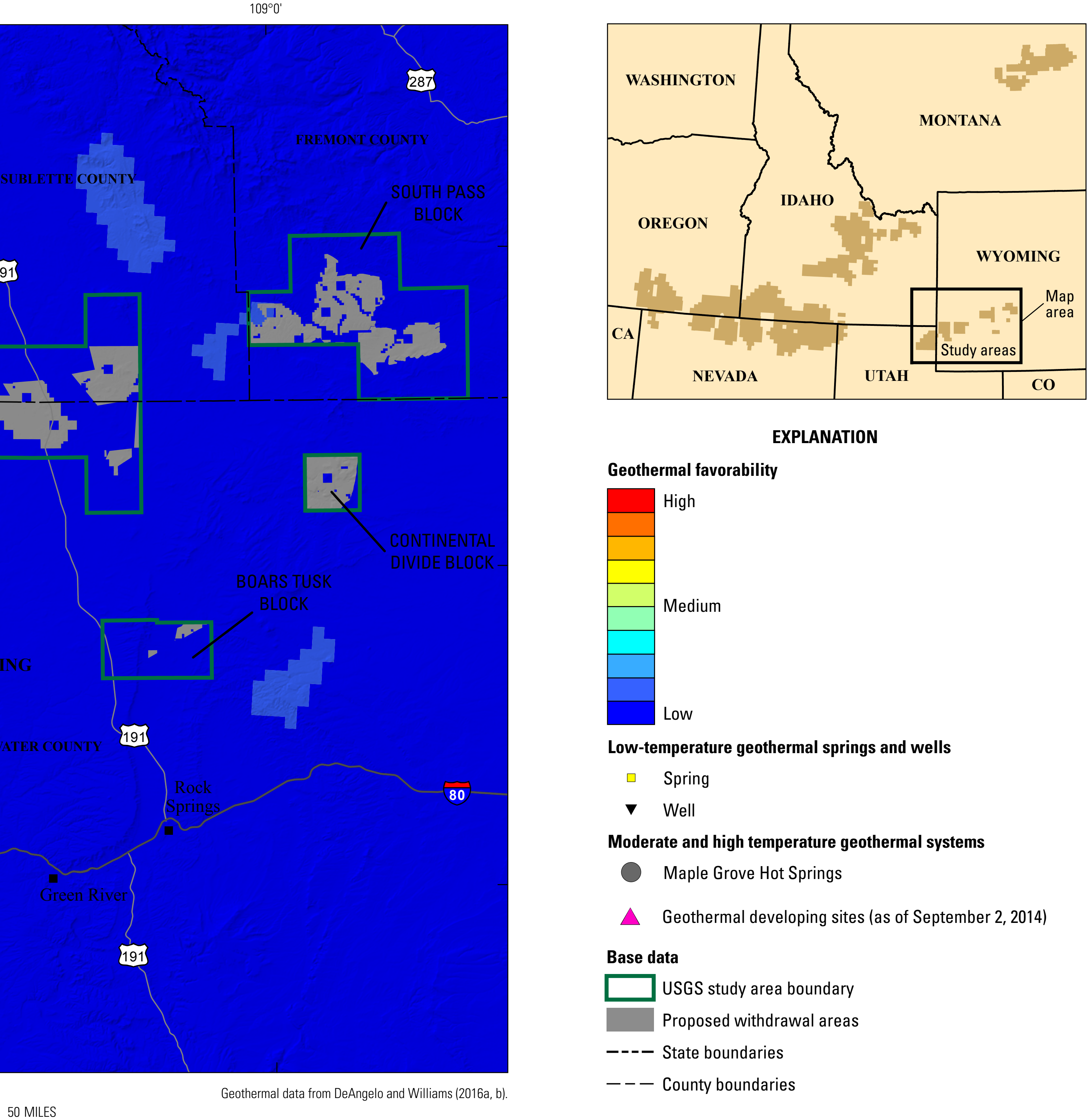
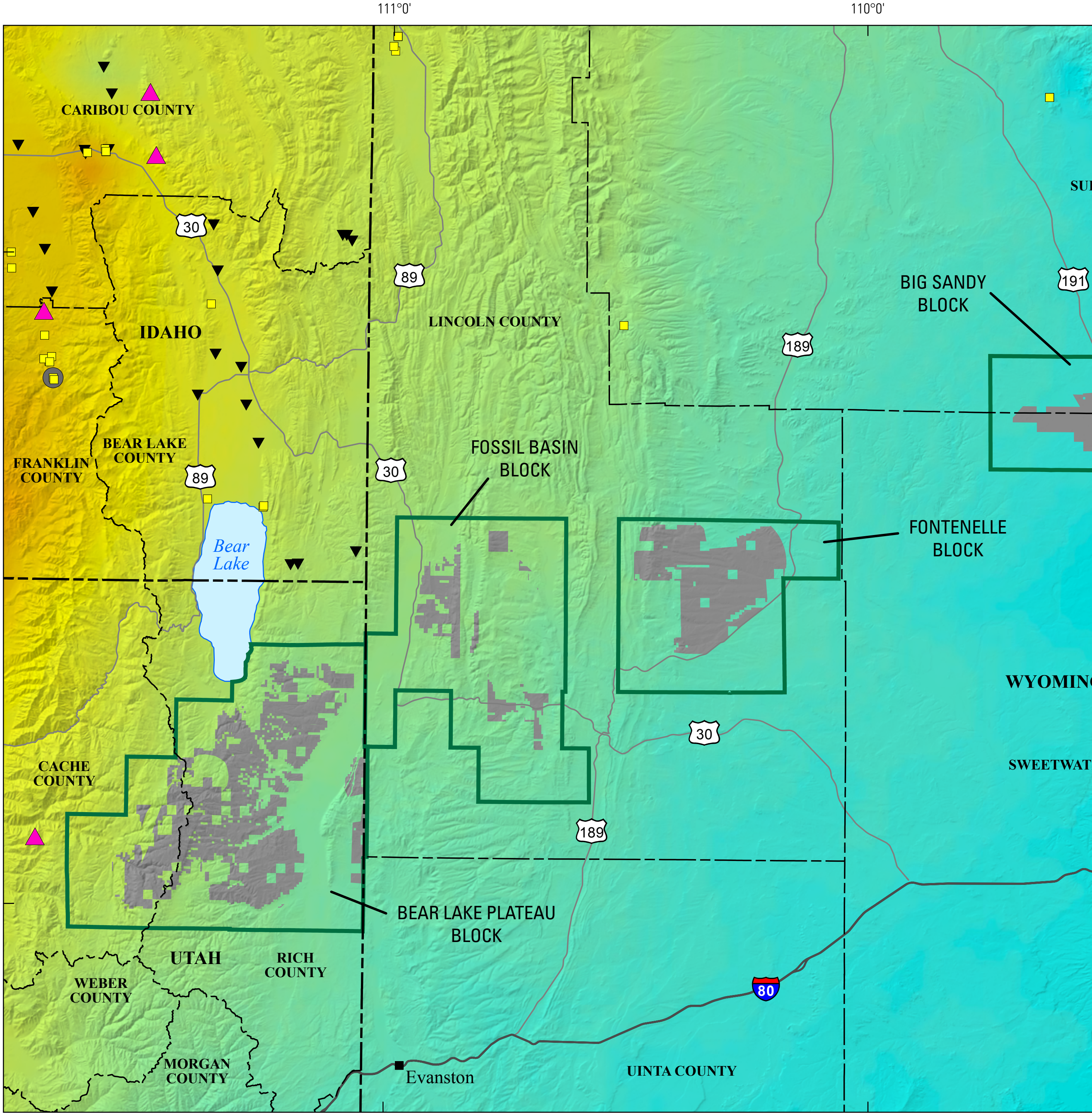



Geothermal data from DeAngelo and Williams (2016a, b).

**Figure 13.** Map showing the locations of low-, moderate-, and high-temperature geothermal systems and geothermal development sites, as well as hydrothermal favorability from the 2008 U.S. Geological Survey (USGS) geothermal assessment for an area encompassing the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah (Williams and DeAngelo, 2008).

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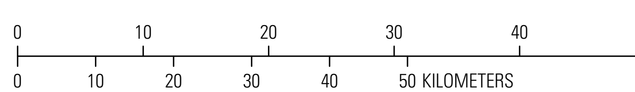


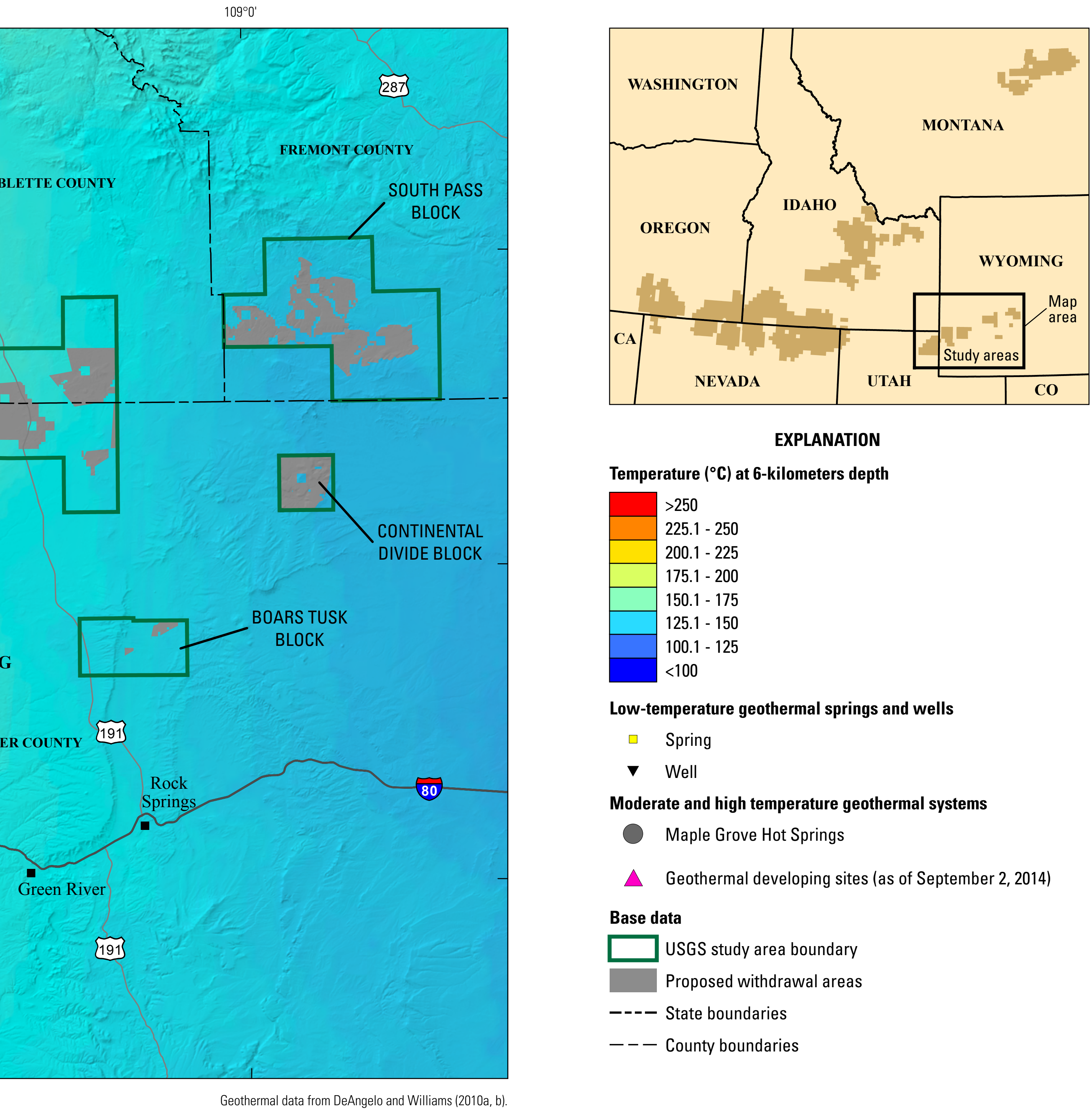



**Figure 14.** Map showing the locations of low-, moderate-, and high-temperature geothermal systems and geothermal development sites, as well as the estimated temperature at 6 km depth, for an area encompassing the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey; °C, degrees Celsius.

the Southwestern and South-Central Wyoming is approximately 5 percent that of the Western U.S. average. As noted above, the western margin of the Bear River Watershed has elevated geothermal potential and drilling indicates water hot enough for electric power generation at the Renaissance site just to the west. However, the western boundary of the Bear River Watershed and the Renaissance site are separated by the Wellsville Mountains, and, as the permeable fault penetrated at Renaissance is most likely confined to the western margin of the Wellsville Mountains, it is not clear that the presence of a potential geothermal resource at Renaissance has significance for the presence or absence of geothermal resources in Bear River Watershed.

Low-temperature geothermal resources of this region were assessed by Reed (1983), with subsequent inventories of low-temperature springs and wells published by Breckenridge and Hinckley (1978), Reed and others (1983), and Lienau and Ross (1996). No springs and wells from these inventories are located within the Utah-Wyoming study areas, although Reed (1983) did note the low-temperature potential associated with thermal aquifers in the greater Green River Basin. These aquifers could be exploited locally for direct-use applications, and it is conceivable that under more favorable commercial conditions, geothermal power demonstration projects similar to the Department of Energy's Rocky Mountain Oilfield Testing Center (RMOTC) Powder River Basin project (described by Anderson, 2010) could be established in the greater Green River Basin. However, no site-specific assessment has been conducted in the greater Green River Basin to quantify the geothermal-resource potential from oil and gas production for which the produced waters are delivered in sufficient quantity and temperature to produce electric power.

In the provisional assessment of EGS resource potential (Williams and others, 2008), the threshhold for EGS viability was established as a minimum temperature of 150 °C at a depth of 6 km (see also Williams and DeAngelo, 2011). Any region below that temperature-depth threshold was not included in the assessment. The region covered by the Southwestern and South-Central Wyoming study area is at or just below that cut-off, and, consequently, cannot be considered as having significant EGS potential. Temperatures at a depth of 6 km across the Bear River Watershed study area range from approximately 150 to 225 °C, which is equivalent to the average for the entire Western United States (fig. 14). Consequently, the Bear River Watershed study area could become a target for EGS development if geothermal production technology becomes commercially viable, but it should be noted that large regions of the Western United States, including northern Nevada, northwestern Utah, and southern Oregon and Idaho, have temperatures at 6 km depth that are well in excess of 250 °C, making them more attractive for first generation EGS development (Williams and DeAngelo, 2011).

## Coal

Coal supplies 33 percent of electrical power in the United States (Energy Information Administration, 2015). Although its percentage of total electrical generation has declined, it will likely continue to be a major source of electrical power in the years to come. Coal on Federal lands is managed by BLM as a leasable solid mineral under the Mineral Leasing Act of 1920. BLM manages coal leasing, as well as other administrative duties related to coal production from Federal coal lands throughout the United States.

### Mineral Description

Coal is a black or dark-brown combustible rock that consists of compressed and carbonized vegetable matter and is used as a fuel.

### Geology and Occurrence in the Study Area

The USGS report of coal fields in the conterminous United States (East, 2013) shows that parts of the Southwestern and South-Central Wyoming and Bear River Watershed study areas are within the Green River and Hams Fork coal regions (fig. 15). These coal regions are both known to have subbituminous to bituminous Tertiary and Cretaceous coal.

The Green River coal region includes the Tertiary and Upper Cretaceous rocks (fig. 16) of the greater Green River Basin (fig. 3). Coal-bearing formations include, from oldest to youngest, the Upper Cretaceous Rock Springs and Almond Formations of the Mesaverde Group; the Upper Cretaceous Lance Formation; the Paleocene Fort Union Formation; and the Eocene Wasatch Formation. These formations have been mined for coal around the Rock Springs Uplift since the mid-1880s (Gardner and Flores, 1989). Currently (2016) the Jim Bridger and Black Butte Mines are active on the eastern side of the uplift and another inactive mine (Stansbury) is on the west side (fig. 15; mine status from Wyoming Department of Environmental Quality, 2015).

The Hams Fork coal region occurs within the thrust belt area. This is an area of very complex geology due to the extreme faulting and steeply dipping beds. Coal-bearing rocks trend north-south, and are bounded by the fault-controlled structure. Four coal fields have been named in the region—Evanston, Greys River, Kemmerer, and McDougal Coal Fields (Glass, 1977). Coal-bearing formations include, from oldest to youngest, the Lower Cretaceous Bear River and Cokeville Formations; the Upper Cretaceous Sage Junction[1], Frontier, Blind Bull, and Adaville Formations; the Cretaceous to Paleocene Evanston Formation; and the Eocene Wasatch Formation (fig. 16). Historically, coal has been mined in the area since

[1]Earlier publications place the Sage Junction Formation at the top of the Lower Cretaceous (Rubey, 1973), but here we follow the Wyoming State Geological Survey's placement in the lowermost part of the Upper Cretaceous section (see Jones and others, 2011) and, thus, an early Late Cretaceous age.

1869 (Glass, 1977). The Adaville and Frontier Formations have produced the most coal. Prospects and mines, mostly concentrated in the Adaville and Frontier Formations, dot the region (Jones and others, 2011). Currently the Kemmerer Mine, working in the Adaville Formation, is the only active mine in the Hams Fork coal region (Wyoming Department of Environmental Quality, 2015).

The USGS has not done a formal quantitative assessment of coal resources within the Southwestern and South-Central Wyoming or Bear River Watershed study areas, but Berryhill and others (1950) estimated resources of 15.96 billion short tons for the Green River coal region and 4.87 billion short tons for the Hams Fork coal region.

## Recent Exploration and Mining Activity

### Southwestern and South-Central Wyoming Study Area

Most of the Southwestern and South-Central Wyoming study area is within the northern part of the Green River coal region (fig. 16) with the exception of the South Pass block, which is underlain by Precambrian rocks of the Wind River Range. As mentioned, those parts of the study area that are within the coal region have never been quantitatively assessed by the USGS for coal resources or coal reserves. Figure 17 is provided for ease of finding the areas mentioned in the following section.

Exploratory drilling for coal occurred in T. 22 N., R. 104 W. (fig. 17) in the early 1970s. Coal was observed in the Paleocene Fort Union and the Cretaceous Almond and Rock Springs Formations of the Mesaverde Group. The Fort Union coal beds are few and mostly 0.9 m (3 ft) thick or less. The Almond coal beds are more numerous and range up to about 1.5 m (5 ft) thick. The Rock Springs Formation has numerous coal beds with thicknesses up to 4.5 m (15 ft). None of the drill holes were within the proposed withdrawal area. Three sections within that township were leased for coal, but the leases have since been closed (Dicken and San Juan, 2016b). The nearest holes to the proposed withdrawal area were drilled in the Fort Union and Almond Formations.

Several prospect pits were also observed in T. 22 N., R. 104 W. (fig. 17) (Jones and others, 2011). These pits were in the Eocene Wasatch Formation, which has no mapped coal in that area. Although the pits are in the study area, they are not within the proposed withdrawal areas.

The National Coal Resource Assessment (Ellis and others, 1999) studied the greater Green River Basin, but the assessed area of that report is south of the Southwestern and South-Central Wyoming study area, and it only assessed the Deadman coal of the Paleocene Fort Union Formation, which is currently being mined on the eastern side of the Rock Springs Uplift (fig. 4).

### Bear River Watershed Study Area

The Bear River Watershed study area is partially within two coal regions (fig. 16). As mentioned above, none of the area has been quantitatively assessed by the USGS for coal resources, although some of the townships within the study area have coal-bearing rocks. For purposes of this discussion, the Bear River Watershed study area can be divided into three blocks—Bear Lake Plateau, Fossil Basin, and Fontenelle (fig. 2).

The Bear Lake Plateau block is not within any coal region. Geologic formations range in age from Paleozoic to Quaternary. None of the formations present is coal bearing.

The Fossil Basin block overlies parts of three coal fields (Kemmerer, Greys River, and Evanston) within the Hams Fork coal region. However, most of the proposed withdrawal areas do not directly overlie coal-bearing rocks because of the geometry of the thrust belt (fig. 4).

The Kemmerer coal field is partially within T. 20 and 21 N., R. 117 W. (fig. 17). The Kemmerer Mine is partially located in those townships (Jones and others, 2011), however, the nearest proposed withdrawal areas are more than 2.8 km (1.75 mi) west of the mine permit area (Wyoming Department of Environmental Quality, 2015). The Federal coal leases extend 0.8 km (0.5 mi) further west than the permit area (Bureau of Land Management, 2016) but are still 1.6 km (1 mi) from the nearest proposed withdrawal areas. As the coal beds at the mine dip steeply to the west, the mine activities are very unlikely to expand westward. From 1983 through 2015, 132,452,275 short tons of coal were produced, and 4,470,864 short tons of coal were produced in 2015 (Mine Safety and Health Administration, 2016).

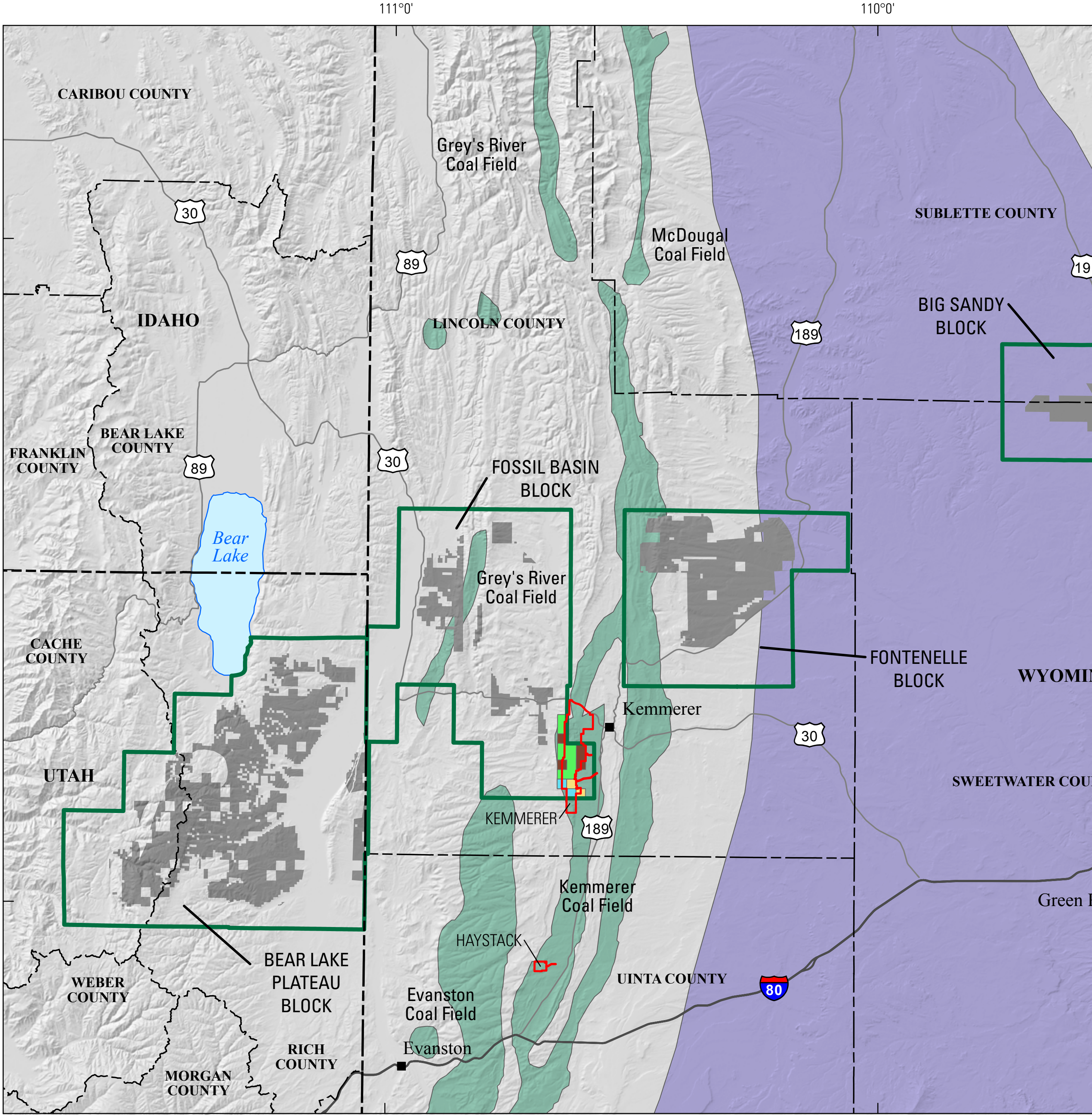
The Greys River Coal Field is partially within five PLSS townships: T. 22 N., R. 118 W.; T. 22 N., R. 119 W.; T. 23 N., R. 118 W.; T. 23 N., R. 119 W.; and T. 24 N., R. 118 W. (fig. 15, 17). No mining has been documented in this coal field (Glass, 1977).

The northern tip of the Evanston Coal Field barely protrudes into the Fossil Basin block in T. 20 N., R. 118 W. (figs. 15, 17). Although a number of old mines exist in the southern part of the coal field, no mining is known to have occurred within the block (Glass, 1977, Jones and others, 2011).

The Fontenelle block straddles the Green River and Hams Fork coal regions (fig. 15). Several small old mines are reported in T. 22 N., R. 115 W. (Jones and others, 2011). There are no known coal reserves within the PLSS townships and none within the proposed withdrawal areas in this block.

## Results of Previous USGS Assessments

A previous assessment has not been undertaken in the study area.

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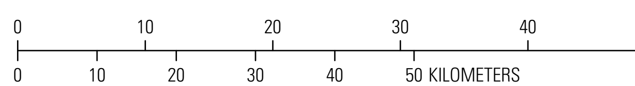
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.



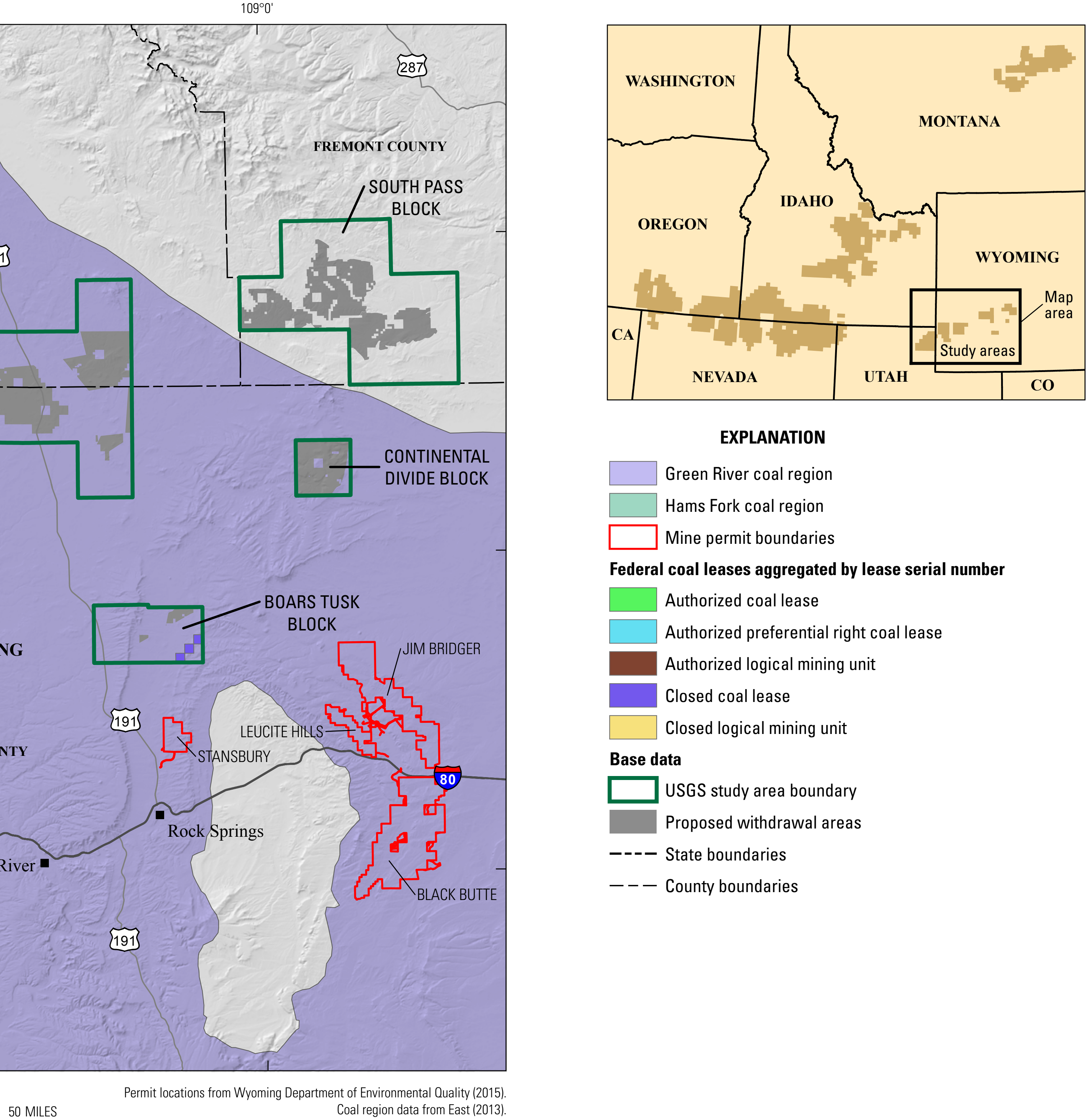



**Figure 15.** Map showing the coal regions (in turquoise and lavender) and mine-permit boundaries (outlined in red) in and near the Southwestern and South-Central Wyoming and Bear River Watershed study areas. USGS, U.S. Geological Survey.

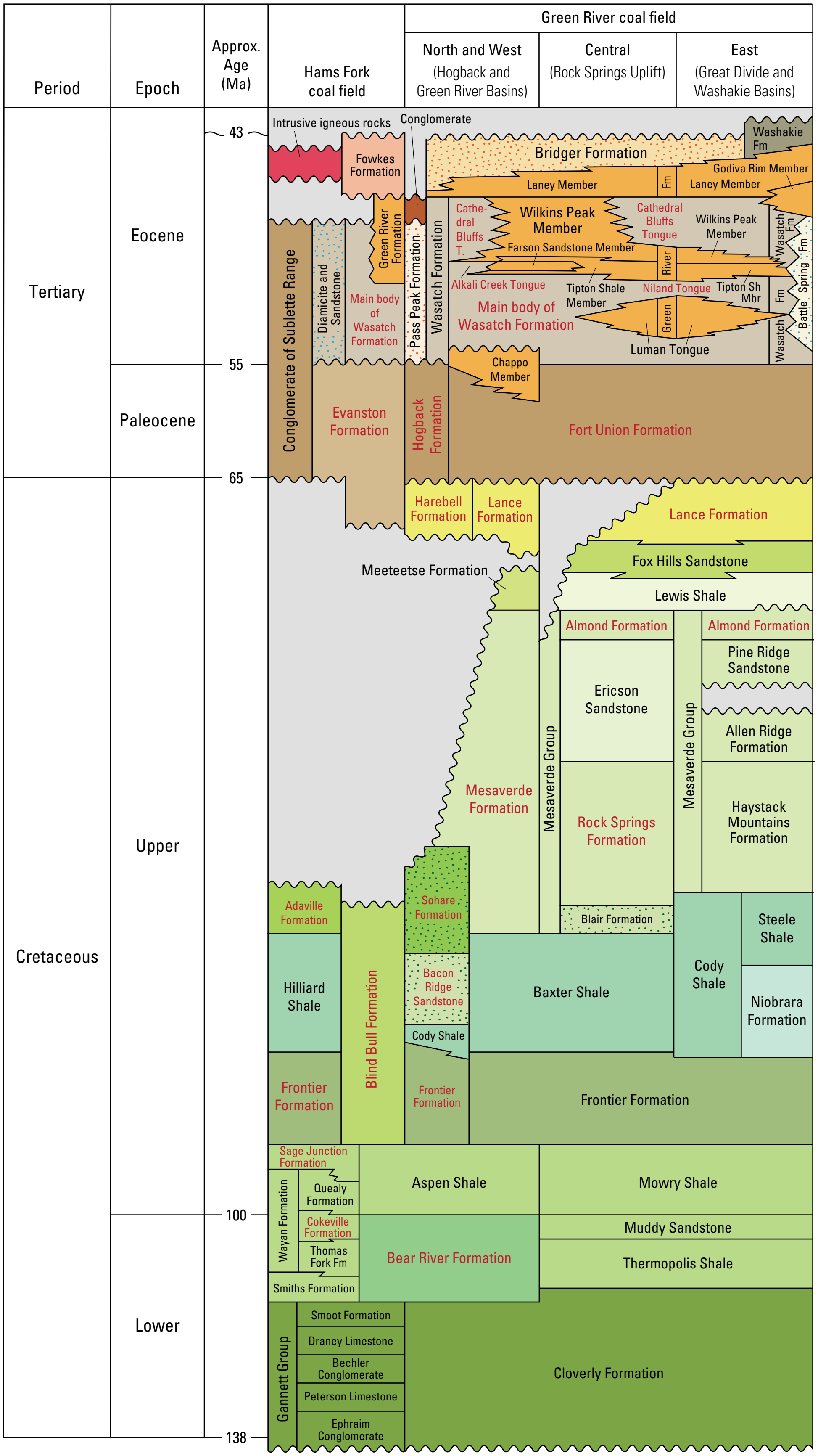



**Figure 16.** Illustration showing stratigraphic column for southwest Wyoming. Formations named in red are coal bearing (after Wyoming State Geological Survey, 2011). Ma, mega-annum or millions of years ago; Fm, Formation, Sh, Shale; Ss, Sandstone; Ls, Limestone; Cgl, Conglomerate.

## Phosphate

Phosphate is classified as a non-energy, solid, leasable mineral by the BLM, which manages it on Federal lands under the Mineral Leasing Act of 1920, as amended (Bureau of Land Management, 2012).

### Mineral Description

Phosphate rock is the primary global source for phosphorus, which is an essential nutrient for all living organisms (Ruttenberg, 2005). Sedimentary phosphate (phosphorite) of marine origin constitutes the majority of phosphate rock used worldwide (Cathcart, 1978). Phosphate rock is initially processed into phosphoric acid or converted into elemental phosphorus ($P_4$) for use in the manufacture of agricultural products such fertilizers, pesticides, and animal feeds (Jasinski and others, 2004; Zhang and others, 2006; Ragheb and Khasawneh, 2010). To a lesser degree, phosphate is used in the manufacture of insecticides, herbicides, flame retardants, semiconductors, fireworks, matches, household cleaning products, and food additives. The principal phosphate mineral in phosphorite is carbonate fluorapatite ($Ca_5\ (PO_4,\ CO_3OH)_3\ (F)$), commonly referred to as francolite (Filippelli and Delaney, 1992). The phosphorus content in phosphate rock and in fertilizer is expressed as phosphorus pentoxide ($P_2O_5$) (Kauwenbergh, 2010). Typically, mined phosphate has a minimum grade of 24 percent $P_2O_5$, has a minimum bed width of 1 m, is laterally extensive, and has minimal overburden (Rogers, 1995). The largest current domestic phosphate production is from phosphorite of Miocene to Pliocene age in Florida and North Carolina, with less production from the extensive area of Permian deposits referred to as the “Western Phosphate Field,”which extends into parts of Idaho, Montana, Wyoming, and Utah (Jasinski, 2016).

### Geology and Occurrence in the Study Area

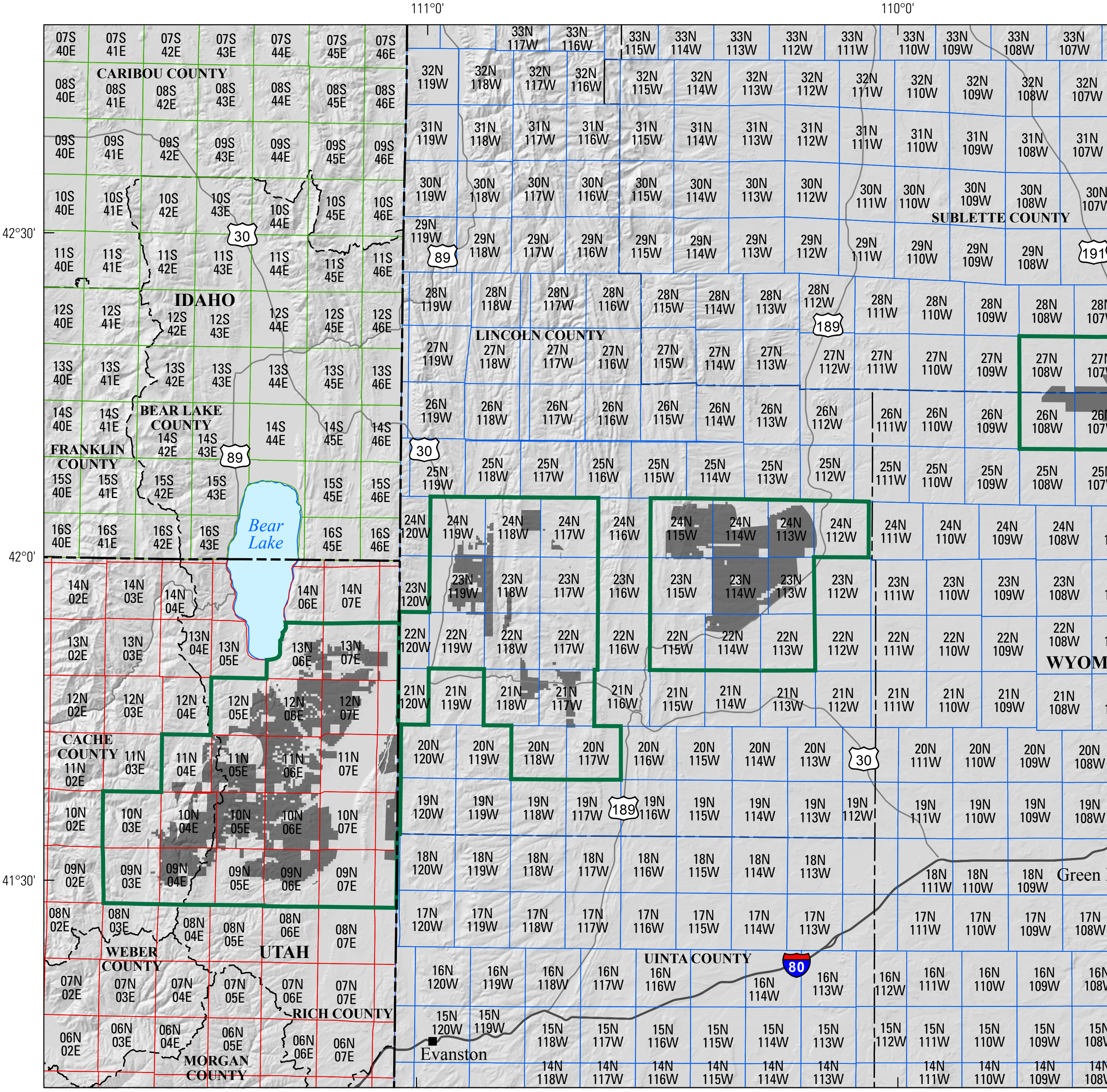
The two most phosphate-rich rock units in the Western Phosphate Field are the Meade Peak Member and Retort Tongue (fig. 18) of the Permian Phosphoria Formation (Mansfield, 1940; Sheldon, 1957; McKelvey and others, 1959; Gulbrandsen and Krier, 1980; Maughan, 1994). Phosphate in the Phosphoria Formation occurs as pelletal phosphorite that is interbedded with organic matter-enriched mudstone and siltstone, limestone, dolomite, and chert (Piper and Link, 2002). Also recognized in parts of the Western Phosphate Field are phosphorites of the Mississippian Deseret Limestone and Woodman Formation in Utah and eastern Nevada (Jewell and others, 2000). These Mississippian deposits, referred to as the Delle-event phosphorites, consist of pelletal phosphatic crusts, pisolitic phosphates, and detrital aggregates of ooidal and other types of phosphate grains (Nichols and Silberling, 1991a, b). Concentrations of $P_2O_5$ in sampled phosphorite beds of the Deseret Limestone range from 23 to 36 percent and, in the Woodman Formation, from 25 to 30 percent (Jewell and others, 2000).

The phosphorites of the Western Phosphate Field differ from the relatively flat-lying, unconsolidated “land-pebble” phosphate of the southeastern coastal region of the United States, as the Western U.S. host lithologies are older, well-indurated, are cross-cut by veins reflecting multiple episodes of injection by heated fluids, contain a series of diagenetic, epigenetic, and supergene mineral assemblages, show evidence of deep burial to the point of catagenesis, were deformed by intense folding and thrust faulting from Late Jurassic or Cretaceous to early Eocene time and later by extensional faulting from Neogene to Holocene time, and were affected by Neogene to Quaternary volcanism associated with the passage of the Yellowstone Hot Spot (Grauch and others, 2004). Such a dynamic history resulted in exposures that tend to follow narrow ridges, consist of steeply dipping beds, and are truncated and offset by extensional faults.

Within the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Permian and Mississippian phosphorites and phosphatic shales transect parts of southwestern Wyoming and northeastern Utah (fig. 19). In Wyoming, the principal source for phosphate is the Meade Peak Member of the Phosphoria Formation, which crops out along much of the northern half of the Tunp Range and over a restricted area near Rock Creek at the southern end of the range (Rubey and others, 1980; Love and Christiansen, 1985). At the southern end of the Tunp Range, near Rock Creek, the exposures of the Phosphoria Formation are approximately 34 m thick (Kivi, 1940). As in the Sublette Range, the Phosphoria Formation in the Tunp Range consists of the Meade Peak, Rex Chert, and Retort Shale Members, with the Tosi Chert absent (McKelvey and others, 1953; Sheldon and others, 1954). McKelvey and others (1953) provide measured sections of the Phosphoria Formation in the middle part of the Tunp Range. At the Rock Creek exposure, Kivi (1940) identified a 2.13-m-thick bed of phosphate rock that averaged 35 percent $P_2O_5$ (Carnes, 2015).

To the north and east of the South Pass block (figs. 2 and 19) of the Southwestern and South-Central Wyoming study area, and southeast of Lander in Fremont County, low- to medium-grade phosphate deposits of the Meade Peak Member and the Retort Tongue of the Phosphoria Formation crop out (fig. 19) along the northeastern flank of the Wind River Range (Carnes, 2015).

Past production in the Wyoming part of the study area was from the Leefe, Cokeville, and South Mountain Mines in Lincoln County (fig. 19). The Leefe Mine, located approximately 48 km west of Kemmerer, produced phosphate rock from the Meade Peak Member of the Phosphoria Formation from 1947 to 1977 (Wyoming Board of Equalization, 1948–1972; Wyoming Department of Revenue, 1973–1978; Jasinski and others, 2004). Productive beds at the Leefe Mine ranged in grade from 25 to 35 percent $P_2O_5$ (McKelvey and others, 1953). The mine included two open pits (Dover, 1995) and yielded more than 4,725,000 tons of phosphate rock

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Boundary data from San Juan and others (2016).
PLSS boundaries from respective state governments, 2016.
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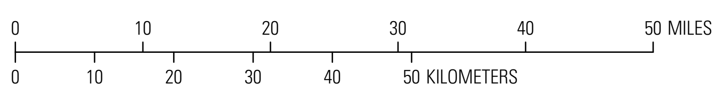
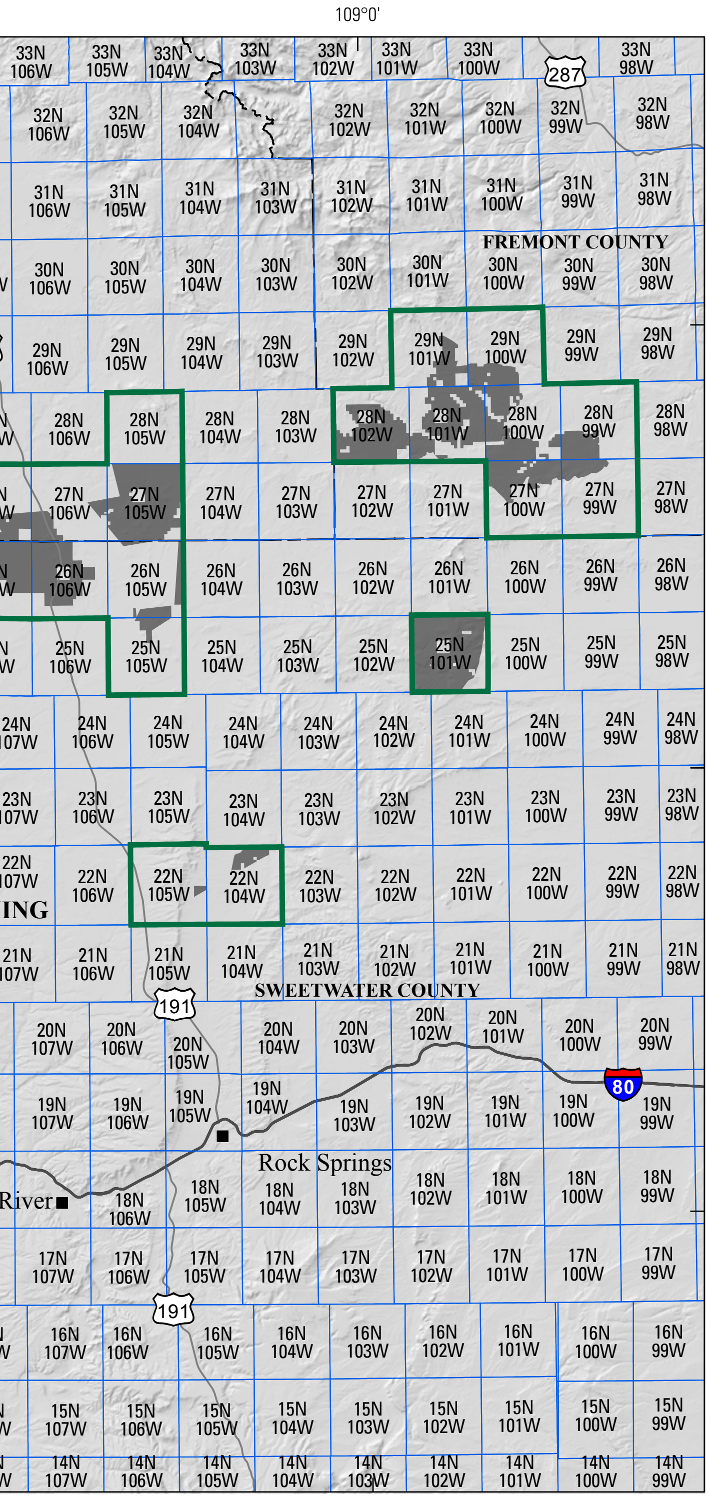
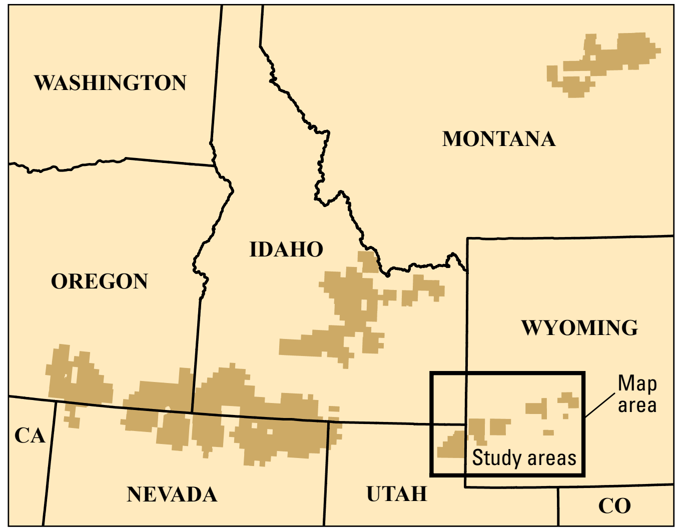
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.






**EXPLANATION**

PLSS townships of Wyoming (6th principal meridian)

PLSS townships of Idaho (Boise meridian)

PLSS townships of Utah (Salt Lake meridian)

**Base data**

USGS study area boundary

Proposed withdrawal areas

State boundaries

County boundaries

**Figure 17.** Map showing the Public Land Survey System (PLSS) township and range grid for the entire region of the Southwestern and South-Central Wyoming and Bear River Watershed study areas. USGS, U.S. Geological Survey.

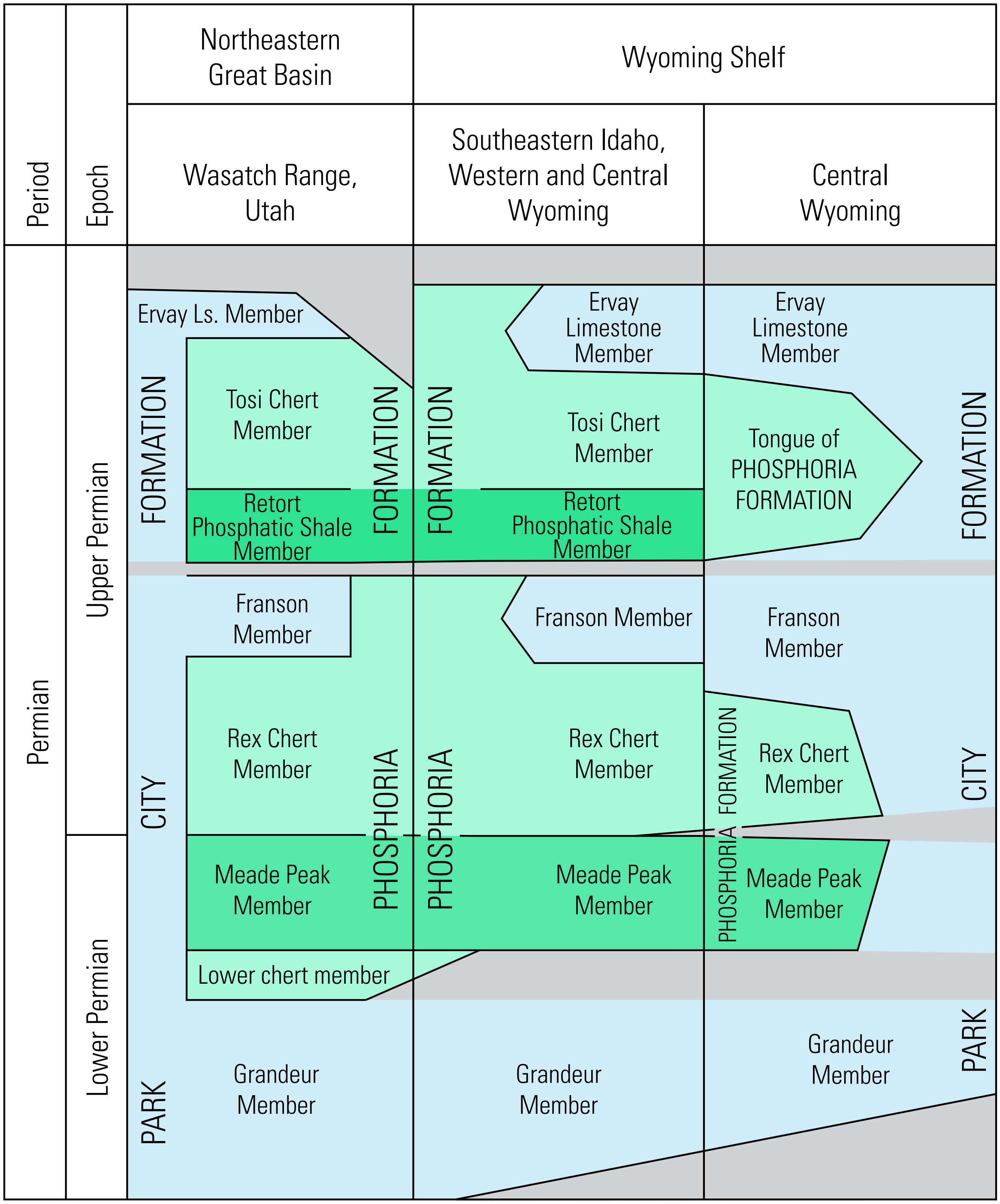



**Figure 18.** Correlation chart of Permian Phosphoria and Park City Formations from the northeastern Great Basin to the Wyoming shelf (from Maughan, 1994).

(Wyoming Board of Equalization, 1948–1972). The Leefe Mine was the last active phosphate mine in Wyoming and closed because of the depletion of phosphate rock resources at the site. After mining operations ceased, phosphate processing continued at the Leefe plant using raw material mined from the Phosphoria Formation in Idaho and Utah into the 1980s (Harris and Hausel, 1984; Carnes, 2015). The Cokeville Mine was an underground mine that operated from 1906 to 1931 (Jasinski and others, 2004). The South Mountain Mine was both underground and open pit and was operated from 1946 to 1951 (Jasinski and others, 2004). Production figures from Cokeville and South Mountain Mines are not available.

In Utah, the principal phosphate deposits are the Permian phosphatic shales of the Phosphoria and intertonguing Park City Formations, which have past and current production, and the Mississippian phosphatic shales of the Delle Phosphatic Member of the Deseret Limestone and equivalent units, which have not been exploited (Tooker, 1992). Early phosphate mines located in the Crawford Mountains in the Utah part of the Bear River Watershed study area include (1) the Arickaree Mine in the Phosphoria Formation that operated from 1907 to 1920 and reopened in 1953; (2) six underground mines that operated from 1960 to 1977; and (3) several other mines that were active from the late 1950s to the mid-1960s (Jasinski and others, 2004).

The only currently active phosphate operation in Utah is outside the study area at the Little Brush Creek Mine (about 113 km south of Rock Springs, Wyoming, and is therefore not shown on figures in this report), which has been operating since 1961 as a surface mine on the south flank of the Uinta Mountains (figs. 3 and 4) in the Permian Phosphoria and Park City Formations (Jasinski and others, 2004). Within the Bear River Watershed study area, past interest in phosphate exploration is indicated by two sections in Rich County just south of the Lake Town phosphate deposits in the Mississippian Humbug Formation and Deseret Limestone that have closed phosphate-prospecting permits (fig. 19).

## Exploration and Mining Activity

Currently, mining in the Western Phosphate Field occurs only in Idaho and Utah in areas outside the Southwestern and South-Central Wyoming and Bear River Watershed study areas. In 2015, production from the entire field was 5.52 million metric tons (Jasinski, 2016). Utah production from Little Brush Creek mine (about 70 mi south of Rock Springs) (Rabchevsky, 1995; Jasinski and others, 2004) was approximately 3.7 million metric tons (Mt) of ore in 2014 (Boden and others, 2015). Production ceased in Wyoming in 1978 owing to depletion of reserves (Jasinski and others, 2004).

## Results of Previous USGS Assessments

The USGS Western U.S. Phosphate project (completed in 2004) was entirely focused on areas outside the Southwestern and South-Central Wyoming and Bear River Watershed study areas. Carnes (2015) provides a comprehensive report on phosphate resources in Wyoming that highlights previously reported medium- to high-grade phosphate rock beds of greater than 0.9 m (3 ft) in thickness and includes analysis of new data points. One of these new data points falls along the margin of the Southwestern and South-Central Wyoming and Bear River Watershed study area. This point is just east of the Middle Fork of Pine Creek in the Tunp Range, Lincoln County, and has a $P_2O_5$ content of >30 percent (Carnes, 2015).

## Trace Elements as Potential Byproducts of Elemental Phosphorus and Phosphoric Acid Production

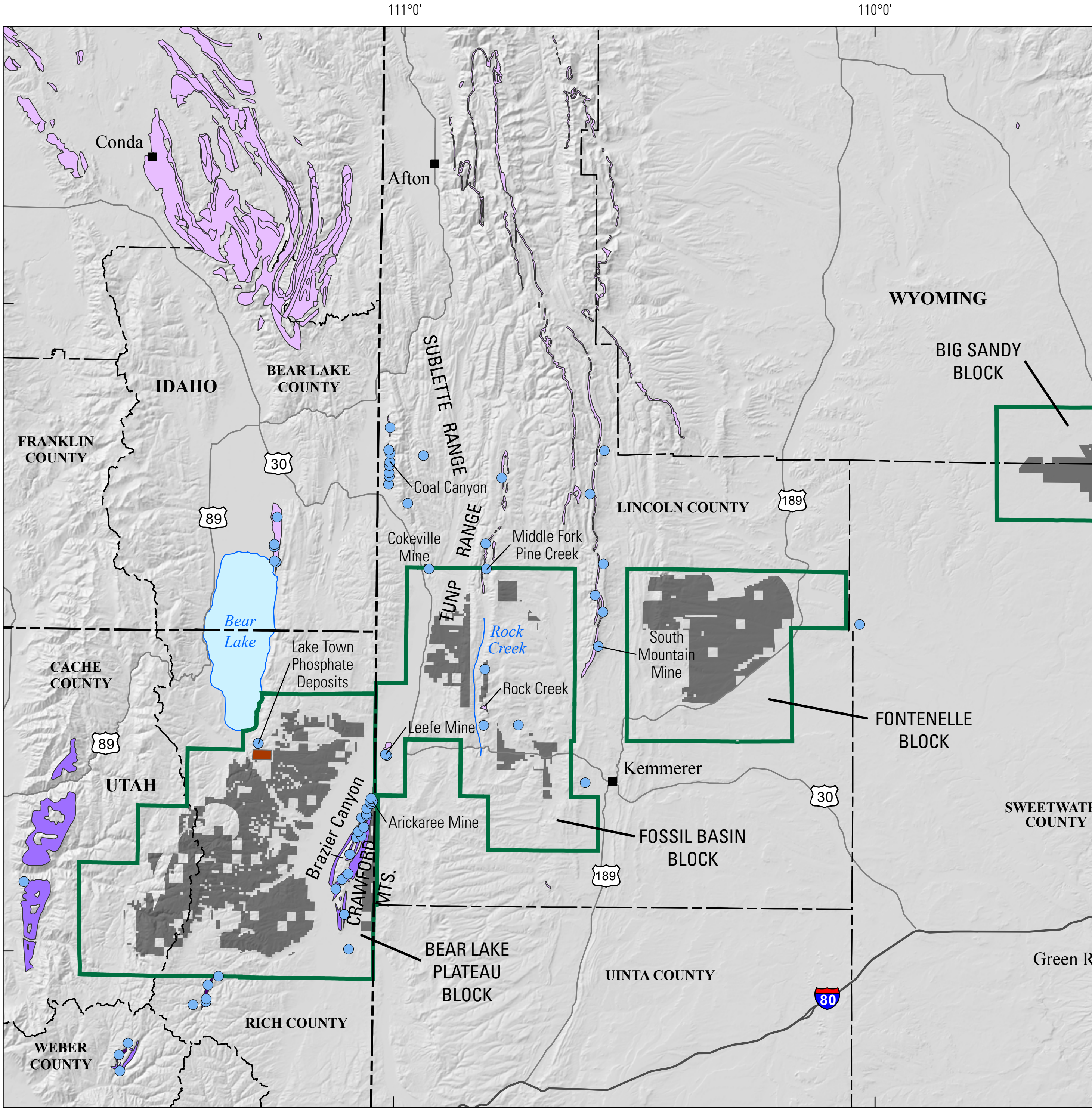
Arsenic, cadmium, chromium, copper, molybdenum, nickel, rare earth elements, selenium, silver, uranium, vanadium, and zinc are found in trace amounts in the Phosphoria Formation (Piper, 2001).

### Vanadium

Within the francolite crystal lattice, $VO_4$ is among the ions that may substitute for $PO_4$ (Cathcart, 1991; Kolodny and Luz, 1992; Jarvis and others, 1994). Vanadium in carbonaceous shales and phosphorite beds of the Phosphoria Formation occurs in trace amounts that exceed the average for marine shales (Fischer, 1962; Maughan, 1994). On average, the vanadium pentoxide ($V_2O_5$) content of phosphate rock of the Phosphoria Formation is about 0.05 percent (500 ppm) (Cathcart and Gulbrandsen, 1973). Maughan (1994) showed that vanadium in the Meade Peak Member ranged from 100 to 1,000 parts per million (ppm) with highest concentration in southeastern Idaho; in the Retort Tongue, vanadium ranged from 100 to 400 ppm with highest concentration in southwestern Montana. Bauer and Dunning (1979) analyzed samples from three measured sections in the Phosphoria Formation at Conda, Idaho; Coal Canyon, Wyoming; and Brazer Canyon, Utah (fig. 19), and found that the highest-grade vanadium occurred in a 1.143-m-thick bed that contained 0.67 percent (6,700 ppm) $V_2O_5$, 2.4 percent $P_2O_5$ and 10 ppm uranium.

In the Afton area in western Wyoming, outside the study area, Love and others (2003) describe vanadium reserves of about 30 million tons of "indicated" vanadium ore that averages 1.1 percent (11,000 ppm) $V_2O_5$, estimated for the shale and mudstone beds in the Meade Peak Member of the Phosphoria Formation. The richest central 0.64 m of the vanadiferous zone is black shale, oolite, and dark-gray mudstone. The vanadiferous zone is remarkably consistent in character, grade, thickness, and lateral continuity throughout the Afton and adjacent 2,590-$km^2$ mountainous area (Love and others, 2003).

Vanadium has been recovered as a by-product of elemental phosphorus and phosphoric acid production (Coleman and Clevenger, 1967). In 1941, Anaconda Copper Mining Company began recovering vanadium as a by-product from phosphate rock in their processing plant at Conda, Idaho

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Central meridian, 110° W., latitude of origin, 37.5° N.
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0 10 20 30 40 5
0 10 20 30 40 50 KILOMETERS

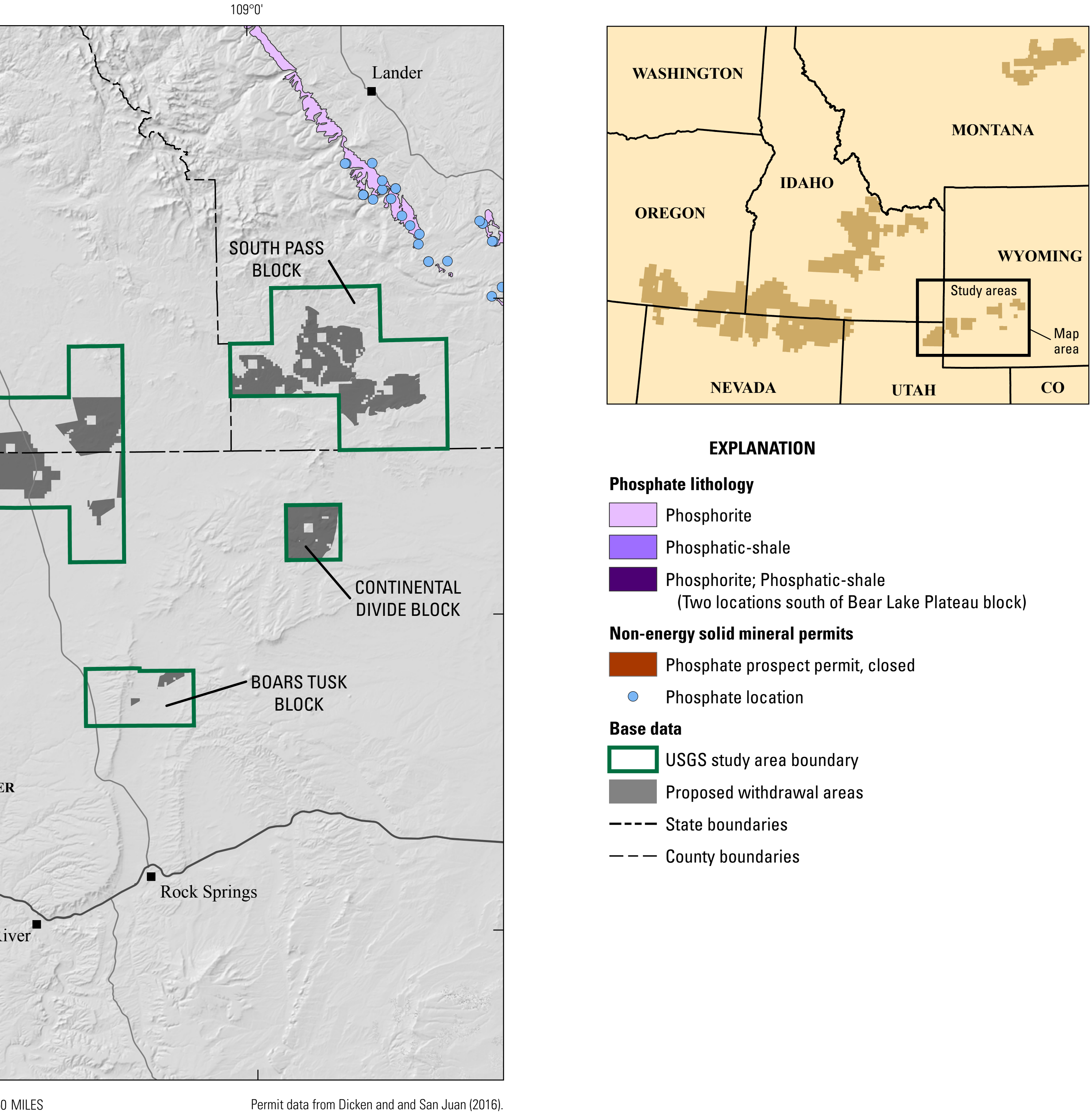



**Figure 19.** Map of the surface extent of Permian and Mississippian phosphorite and phosphatic shale in the Southwestern and South-Central Wyoming and Bear River Watershed study areas (Stoeser and others, 2007; Ludington and others, 2007), showing study area boundaries and U.S. Geological Survey (USGS) Mineral Resources Database (MRDS) past producing phosphate mines, prospects, and sites.

(Love and others, 2003). At a nearby plant near Soda Springs, Idaho, vanadium has been recovered from vanadium-rich ferrophosphorus, a product of the electric reductor furnaces used to manufacture elemental phosphorus (Bauer and Dunning, 1979). Several companies have developed processes by which vanadium is recovered as a by-product from phosphoric acid (Fisher, 1962; Bauer and Dunning, 1979; Guirguis, 1985). In 1985 and 1986, the Phosphoria Formation was the chief U.S. domestic source of vanadium (Kuck, 1985; Goldberg and others, 1992). By 2003, domestic vanadium production was solely from recovery from various industrial waste materials such as fly ash, petroleum residues, spent catalysts, and vanadium-bearing iron slag (Magyar, 2003).

### Uranium

Uranium is among the ions that can substitute for calcium in the francolite crystal lattice (Cathcart, 1991; Kolodny and Luz, 1992; Jarvis and others, 1994). Marine phosphorite deposits contain 6 to 120 ppm uranium, and organic phosphorites have as much as 600 ppm (Ragheb and Khasawneh, 2010). In the past, when demand was high, uranium was commercially recovered as a by-product from phosphoric acid, an intermediate product of processing phosphatic rock (Kouloheris, 1979; Botella and Gasós, 1989; Ragheb and Khasawneh, 2010; Ulrich and others, 2014). There is renewed interest in uranium recovery from phosphorite (Ulrich and others, 2014).

Uranium content of the Permian Phosphoria phosphorites from Idaho, Montana, Utah, and Wyoming ranges from 0.002 to 0.021 percent (20 to 210 ppm), averaging 0.009 percent (90 ppm) (Gulbrandsen, 1966; Cathcart, 1978).

### Rare Earth Elements

Rare earth elements (REEs) are among the ions that can substitute for Ca in the francolite crystal lattice (Cathcart, 1991; Kolodny and Luz, 1992; Jarvis and others, 1994). Lanthanum occurs in trace amounts in the Phosphoria Formation. In the Meade Peak Member, lanthanum concentrations range from 50 to 300 ppm, with highest concentrations in southeastern Idaho. In the Retort Member, lanthanum concentrations range from 50 to 350 ppm, with the highest concentrations in southwestern Montana (Maughan, 1994).

Altschuler and others (1967) recognized the potential to recover REEs as a by-product from phosphoric acid processed from phosphate rock from sedimentary deposits. Subsequent research maintains that extraction of REEs from sedimentary phosphate rock could be as high as 100 percent (Emsbo and others, 2015).

# Potash

Potash is a water-soluble compound of potassium (K) formed by geologic and hydrologic processes. Along with phosphorous and nitrogen, potash is an essential nutrient necessary to sustain plant life. In addition to fertilizer, potash has been used for the bleaching of textiles, glass manufacture, and soap production.

## Mineral Description

The major potash resources of the world are evaporite-related deposits that principally occur as potash salts such as sylvite (KCl), and sylvinite (KCl+NaCl) (Garrett, 1996). They generally co-occur with chlorides, sulfates, and halite in evaporite sequences (Orris and others, 2014). Potash derived from groundwater- and lake-brine can also be harvested at the surface from man-made solar evaporation ponds. Industrial phrases used to describe potash varieties are muriate of potash (MOP) and sulfate of potash (SOP). MOP is composed of potassium chloride (KCl), whereas SOP is composed of potassium sulfate ($K_2SO_4$).

Non-evaporite sources of potash, which are often not economical to mine today for use as fertilizer, include potassium-bearing silicate minerals that occur in igneous rocks. Alkalic igneous rocks that are high in sodium and potassium and contain minerals such as leucite ($K(AlSi_2O_6)$) and nepheline ($Na_3KAl_4Si_4O_{16}$) were investigated in the early 1900s as a possible source for potash when it was in short supply in the United States (Schulz and Cross, 1912). Another source of SOP is the mineral alunite ($KAl_3(SO_4)_2(OH)_6$), which occurs in veins and hydrothermally altered rocks and in sedimentary deposits (Hall, 1978). Alunite is a relatively minor source of SOP and commonly not economical to mine, and so it was not included as part of the global potash assessment described in Orris and others (2014).

## Geology and Occurrence

An important source of potash salt production in the Western United States is derived from brine that has formed in intracontinental, closed basins (Orris, 2011). Closed basins are those having restricted surface-water inflow and outflow. The Basin and Range physiographic province, characterized by lowland basins and surrounding adjacent mountain ranges, has a geography in which closed-basin lakes form and brines can subsequently evolve. During the Pleistocene, large, closed-basin lakes formed in the Western United States in the Basin and Range—the former Lake Bonneville is an example of one such lake. In the case of Lake Bonneville, water became saline and concentrated in potash during evaporation as lake levels declined from about 15,000 years before present (B.P.) to the Holocene. Today, groundwater that is a remnant of the former Lake Bonneville is pumped from shallow wells near Wendover, Utah. The groundwater is transferred to solar evaporation ponds where it is evaporated at the surface, and potash is recovered through a series of industrial processing and refining techniques.

No closed-basin brine-type potash occurrences are known within the Southwestern and South-Central Wyoming or Bear River Watershed study areas, but a potash tract identified in

Orris and others (2014) does occur within the Basin and Range Province. The eastern edge of the tract is approximately 10 km (6 mi) west of the westernmost part of the Bear River Watershed study area. This possible potash occurrence is classified as a closed-basin brine type and coincides with the potash tract defined by the maximum extent of the former Lake Bonneville shoreline (Orris, 2014).

Nontraditional and commonly non-economic potash sources can be derived from silicate rocks and minerals that occur at or near the Earth's surface. Alkalic igneous rocks that have high potassium concentrations are exposed in the Leucite Hills northeast of Rock Springs, Wyoming. A potash prospect that contains the silicate mineral leucite is located near the Leucite Hills within the Southwestern and South-Central Wyoming study area in Sweetwater County, Wyoming. The prospect is about 5 km (3 mi) north of the Boars Tusk block (fig. 2) at 109.192 longitude, 41.964 latitude (Fernette and others, 2016a; U.S. Geological Survey, 2016; Harris and others, 1985). No other occurrences of potash derived from alkalic igneous rocks are known in the study area.

### Exploration, Development, or Mining and Results of Previous USGS Assessments

There is no known exploration, development, mining, or assessments of potash in the study area.

## Locatable Minerals

Locatable minerals include both metallic minerals and nonmetallic minerals administered by BLM on Federal lands under the Mining Law. The law provides for the filing of mining claims to explore for and produce these minerals (Bureau of Land Management, 2012).

For the Southwestern and South-Central Wyoming and Bear River Watershed study areas, metallic locatable minerals include gold (and silver), copper (and silver), uranium, titanium, and iron. The first three were assessed in detail. Titanium and iron potential are discussed, but no tract for potential and certainty rating is given. Likewise, diamonds and dolomite, nonmetallic locatable resources, are discussed, and a tract for potential and certainty rating is presented for diamonds.

Table 6 lists how many active and closed claims and what type of claims are within the proposed withdrawal area. In the proposed withdrawal areas within the Southwestern and South-Central Wyoming study area there are no active lode claims, but there are 13 active placer claims. Most of those are presumed to be in the Dickie-Spring–Oregon Gulch area, although there are no geographic descriptions detailed enough to pinpoint the exact location (table 6, fig. 20). There are no active claims in the Bear River Watershed study area for either lode or placer deposits (fig. 20).

Table 7 shows surface management permits for the proposed withdrawal area within the study area. There are two types of permits. One is a plan of operations, and the other is a notice of intent. The unique number of cases is a summary of all permits within the proposed withdrawal area. The specific status (authorized, pending, closed, cancelled, expired, rejected, or withdrawn) further explains how many of each type of permit are within the proposed withdrawal area. Only one plan of operations for locatable minerals is pending for the entire study area: in the South Pass block of the Southwestern and South-Central Wyoming study area, where there are also two closed plans (table 7; fig. 21). There are no locatable mineral operations in the Bear River Watershed study area (table 7; fig. 21).

Surface-management authorizations are tallied in more detail by commodity type in table 8. Active permits are those that have a status of authorized or pending. In the entire study area, there is just one active surface-management authorization (table 8, fig. 21). It is for a placer gold operation on the

**Table 6.** Summary of mining claims for locatable minerals in sections containing the proposed withdrawal area within the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah.

[Source: Bureau of Land Management LR2000 database, March 6, 2016. The number of cases is for the complete section that includes a proposed withdrawal area]

***A.*** Southwestern and South-Central Wyoming study area, Wyoming.

| Area | Active lode claims | Closed lode claims | Active placer claims | Closed placer claims | Active millsites | Closed millsites |
|---|---|---|---|---|---|---|
| Sections containing proposed withdrawal area | 0 | 2,321 | 13 | 621 | 0 | 0 |

***B.*** Bear River Watershed study area, Wyoming and Utah.

| Area | Active lode claims | Closed lode claims | Active placer claims | Closed placer claims | Active millsites | Closed millsites |
|---|---|---|---|---|---|---|
| Sections containing proposed withdrawal area | 0 | 38 | 0 | 56 | 0 | 12 |

Sweetwater River near South Pass in Fremont County, Wyoming, although it is not known if the site is on the main river or a tributary stream.

Locatable minerals are present in scattered areas across the study area (table 9, fig. 22). Within the proposed withdrawal areas, few deposits have produced. Within the greater study area, there have been a few productive mines (table 9). Production for many producing properties is aggregated so as to not release proprietary corporate data.

## Mineral Potential

This report uses the BLM mineral-potential classification system, which categorically ranks areas according to potential and certainty (appendix 1). For example, areas can be assigned high, moderate, and low mineral resource potential according to the degree of likelihood that geologic processes operated in an area in such a way as to permit accumulation of resources. Level of certainty is ranked A through D, least confident to most confident, based on indirect or direct evidence about the existence of mineral resources. The definitions of these levels of resource potential are given in a companion report (Hammarstrom and Zientek, 2016). In this classification, potential refers the presence (occurrence) of a concentration of one or more energy and (or) mineral resource. It does not imply potential for profitable development and (or) extraction of the mineral resource(s).

A geologically based approach is used to assess mineral resource potential in the study areas. The science behind the USGS assessment approach relies on the concept that mineral

**Table 7.** Summary of status and number of 43 CFR 3809 surface-management authorizations for locatable minerals in the proposed withdrawal area within the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah.

[Source: Bureau of Land Management LR2000 database, accessed March 6, 2016. The number of cases is for the complete section that includes a proposed withdrawal area. ND, no data]

***A.*** Southwestern and South-Central Wyoming study area, Wyoming.

| Permit type | Number of unique cases | Active | Authorized | Pending | Closed | Cancelled | Expired | Rejected | Withdrawn |
|---|---|---|---|---|---|---|---|---|---|
| Plan of operations | 3 | ND | ND | 1 | 2 | ND | ND | ND | ND |
| Notice of intent | 15 | ND | ND | ND | 15 | ND | ND | ND | ND |

***B.*** Bear River Watershed study area, Wyoming and Utah.

| Permit type | Number of unique cases | Active | Authorized | Pending | Closed | Cancelled | Expired | Rejected | Withdrawn |
|---|---|---|---|---|---|---|---|---|---|
| Plan of operations | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Notice of intent | ND | ND | ND | ND | ND | ND | ND | ND | ND |

**Table 8.** Active 43 CFR 3809 surface-management authorizations summarized by commodity in the proposed withdrawal area within the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah.

[Source: Bureau of Land Management database, March 6, 2016. The number of cases is for the complete section that includes a proposed withdrawal area. ND, no data]

***A.*** Southwestern and South-Central Wyoming study area, Wyoming.

| Commodity | Number of active notices | Number of active plans of operations |
|---|---|---|
| Gold, placer | 0 | 1 |

***B.*** Bear River Watershed study area, Wyoming and Utah.

| Commodity | Number of active notices | Number of active plans of operations |
|---|---|---|
| ND | ND | ND |

**Table 9.** Mineral deposits, mines, and important exploration prospects that occur in or near (within 500 meters of) the Southwest and South-Central Wyoming study area, Wyoming.

[Name, (alternate name); Au, gold; O, orogenic low-sulfide gold-quartz vein type; PlP, paleoplacer; P, placer; PP, past producer; R, resource]

| Site name | Site type | Latitude | Longitude | Commodities | Deposit type | Active in past 10 years | Resource and production information |
|---|---|---|---|---|---|---|---|
| Caribou | Mine | −108.72 | 42.51 | Au | O | N | PP |
| Carissa | Mine | −108.79 | 42.47 | Au | O | N | PP, R |
| Carrie Shields | Mine | −108.78 | 42.46 | Au | O | N | PP |
| Diana | Mine | −108.73 | 42.50 | Au | O | N | PP |
| Dickie Springs-Oregon Gulch | Exploration | −108.83 | 42.30 | Au | PlP | ? | Potential resource |
| Doc Barr | Mine | −108.76 | 42.47 | Au | O | N | PP |
| Duncan | Mine | −108.75 | 42.48 | Au | O | N | PP |
| Empire State (B&H) | Mine | −108.76 | 42.47 | Au | O | N | PP |
| Franklin | Mine | −108.81 | 42.46 | Au | O | N | PP |
| Garfield (Buckeye) | Mine | −108.74 | 42.51 | Au | O | N | PP |
| Ground Hog | Mine | −108.75 | 42.49 | Ag | O | N | PP |
| Mary Ellen | Mine | −108.74 | 42.48 | Au | O | Y | PP |
| Midas | Mine | −108.73 | 42.50 | Au | O | N | PP |
| Rock Creek Placers | Placer Mine | −108.74 | 42.51 | Au | P | N | PP |
| Rose | Mine | −109.28 | 42.38 | Au | O | N | PP |
| Soules and Perkins | Mine | −108.73 | 42.50 | Au | O | N | PP |
| St. Louis | Mine | −108.73 | 42.48 | Au | O | N | PP |

deposits can be classified into groups or types based on common characteristics and associations (Skinner and Barton, 1973). A given mineral deposit type will have characteristic ore body geometries, tonnage and grade distribution, and rock and mineral properties that determine if the occurrence or deposit fits a deposit type or model. Deposits of a given type are expected to have a common mode of genesis (Eckstrand, 1984). The genetic foundation of deposit types informs the assignment of mineral resource potential categories. The companion report (Hammarstrom and Zientek, 2016) includes short descriptive models for the deposit types assessed in the SaMiRA reports.

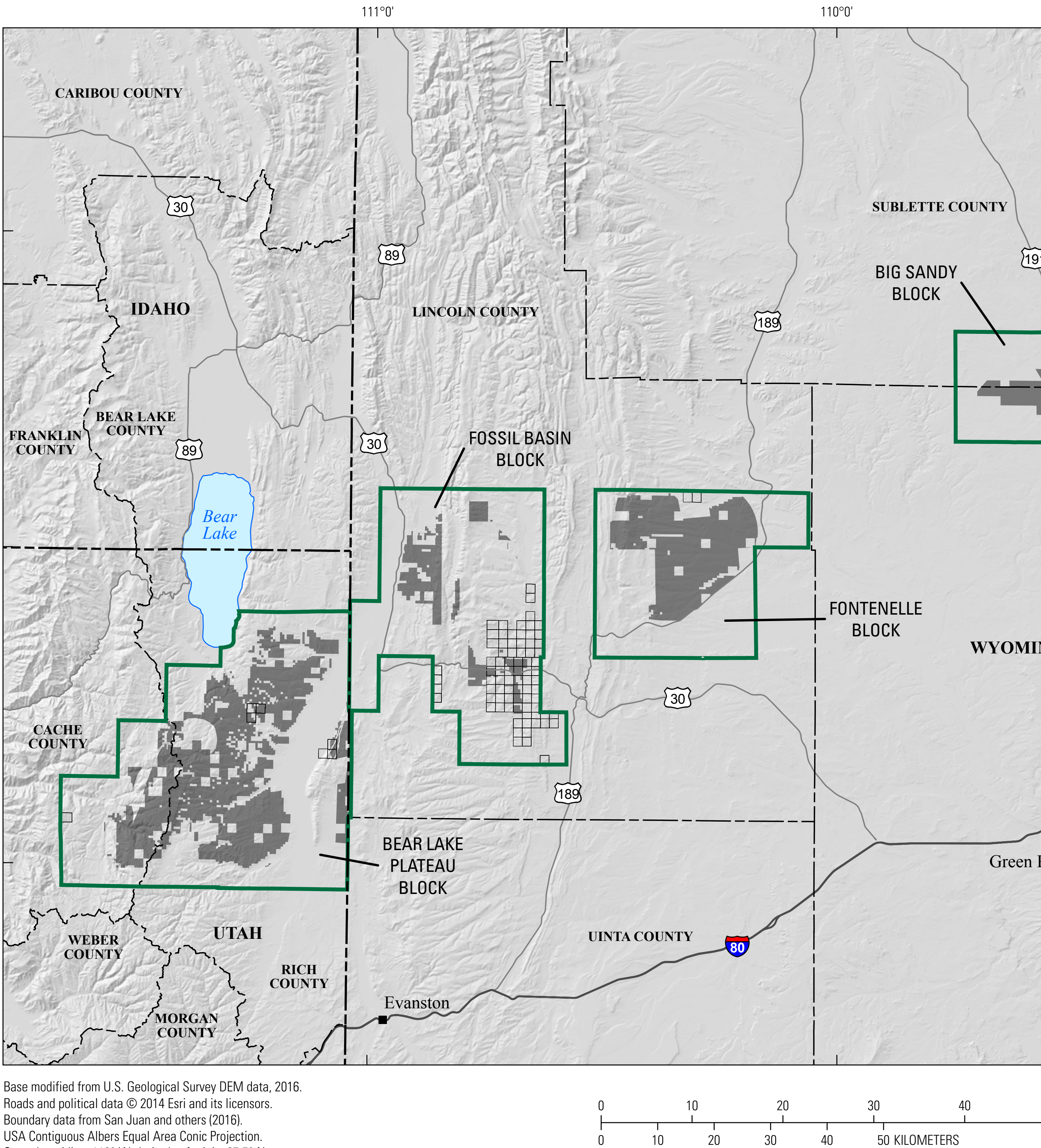
Mineral deposit types can be grouped into larger mineral systems. Mineral systems models organize ideas about how different mineral deposit types relate to regional-scale movements of energy and mass in the Earth, allowing deposit types to be related to geology and tectonics at many scales. The discussion of mineral potential in this report is organized by mineral systems and their related deposit types (Hammarstrom and Zientek, 2016, table H1). In each section, the mineral system is briefly described, followed by a summary of the geology and occurrence of deposit types related to the mineral system in the study area, a description of exploration and mining history, and discussion of the potential for the occurrence of undiscovered deposits. Each section is organized by deposit type.

## Metallic Locatable Minerals

Of the seven blocks in Wyoming and northeastern Utah that contain proposed withdrawal areas (fig. 2), only the South Pass, Fossil Basin, and Bear Lake Plateau blocks have potential for any locatable metallic deposits that can be rated for moderate or high potential within specific tracts. Tracts are presented for three types of gold (Au) deposits and for a single type of copper deposit.

No tract is presented for iron deposits in Algoma-type banded iron formations because, though the large Atlantic City iron mine is immediately north of the South Pass block, and a resource of some 331 million short tons of 22 to 35 percent Fe remained when the mine closed in 1983 (Anonymous, 1960; Bayley, 1963, p. C10–C1; Hausel, 1991, p. 28–29), the iron formation is not known to extend into the land proposed for withdrawal (Bayley, 1963, plate 1; Hausel, 1991, plate 1).

Deposits of heavy-mineral sands that formed in coastal environments almost certainly underlie parts of the proposed withdrawal area of both study areas. However, these deposits are not considered to be economically viable at this time, because they are in lithified Upper Cretaceous sandstones and would require crushing and other processing to liberate the heavy minerals. It serves no purpose to conduct an assessment of those deposits at this time.

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Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

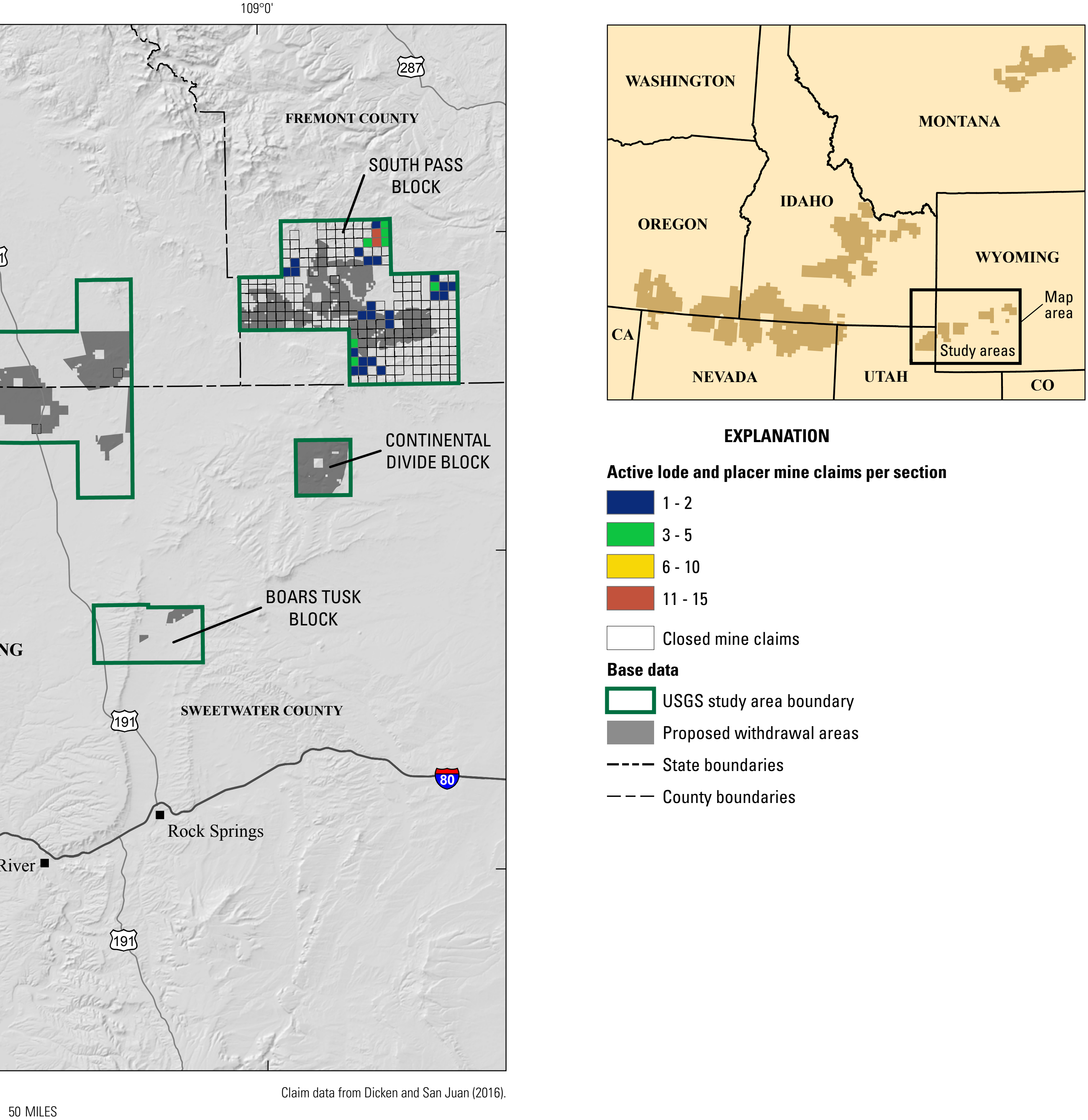
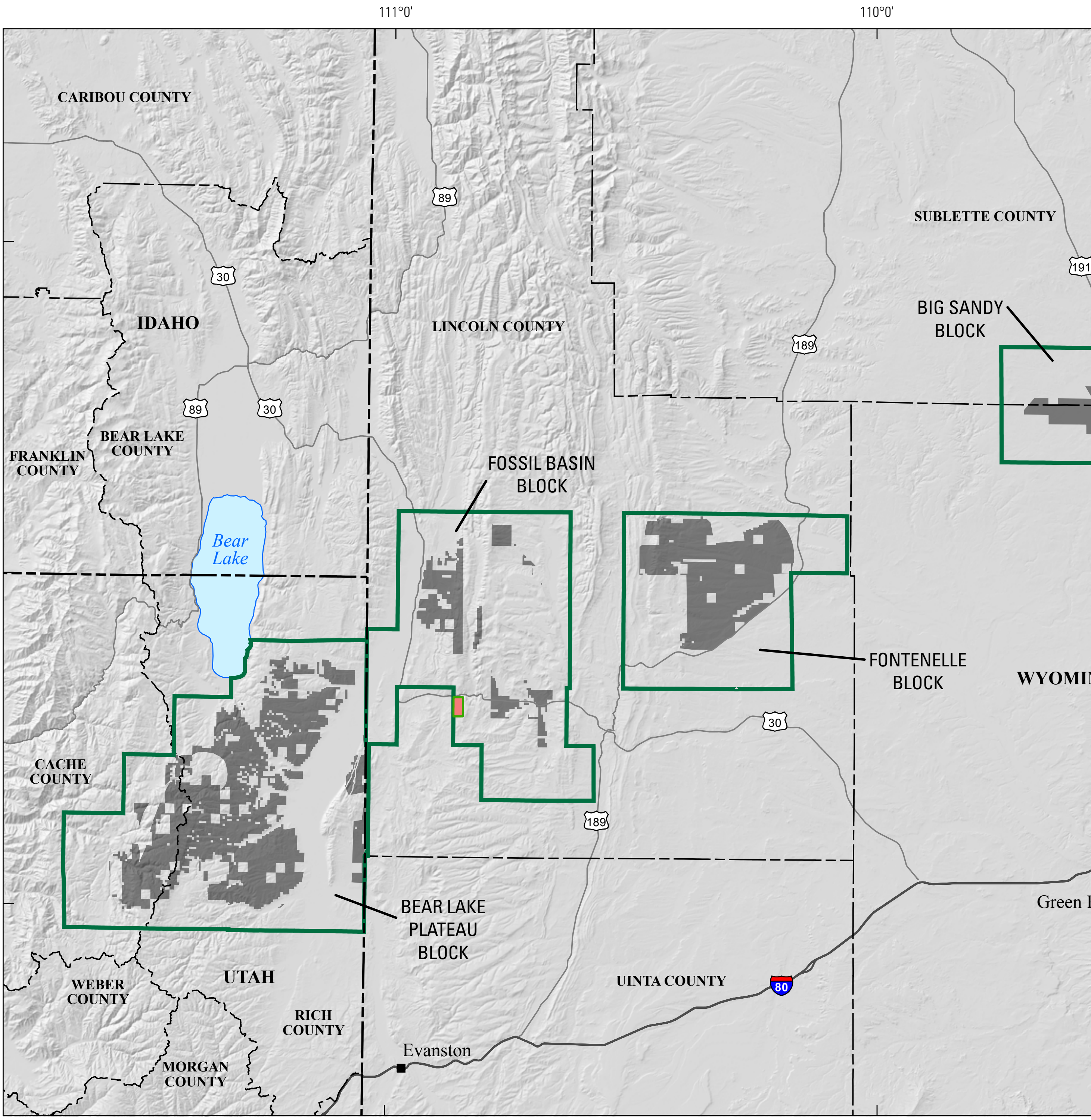



**Figure 20.** Map showing active and pending mine claims for locatable commodities in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.

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0 10 20 30 40

0 10 20 30 40 50 KILOMETERS

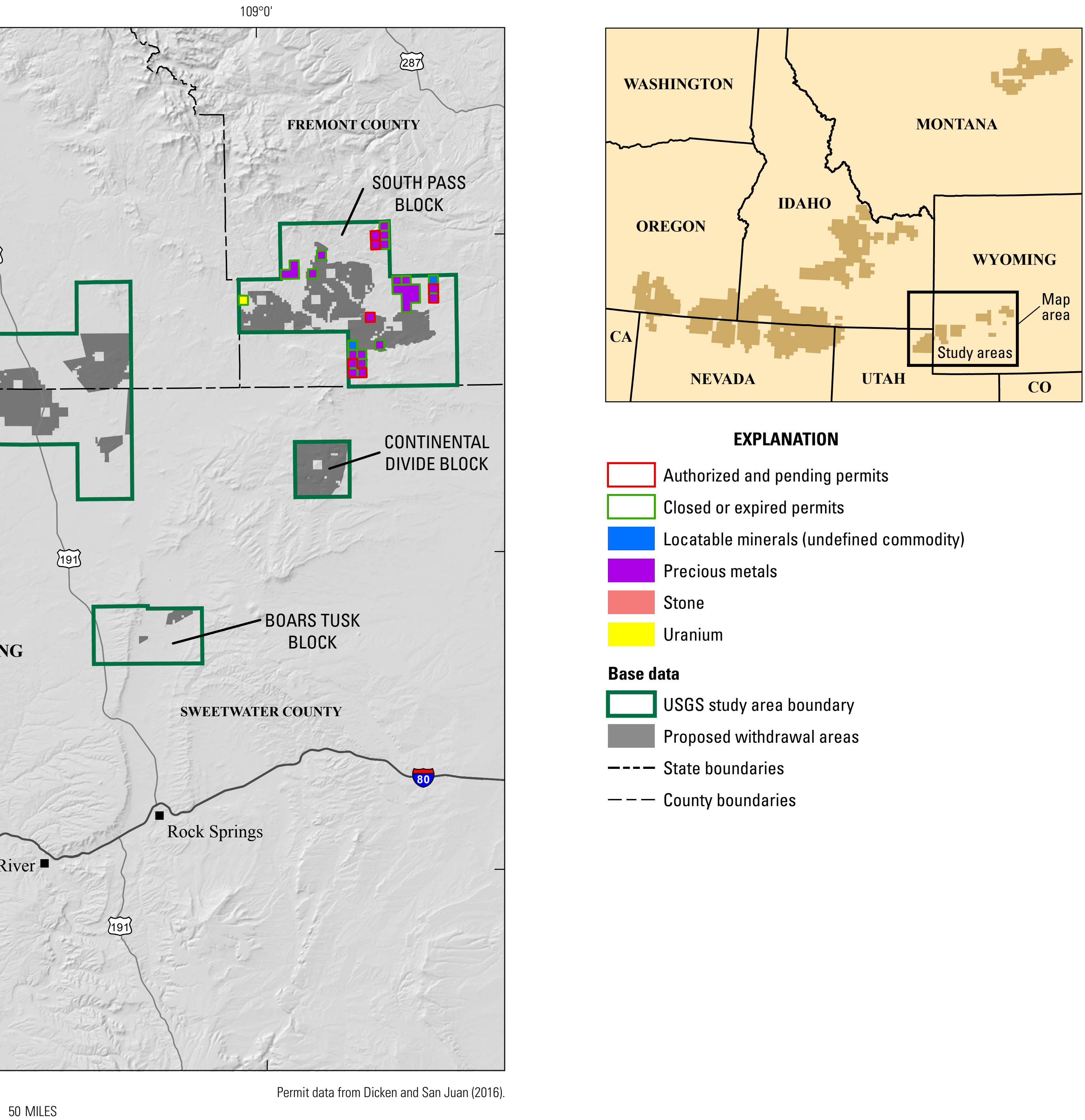
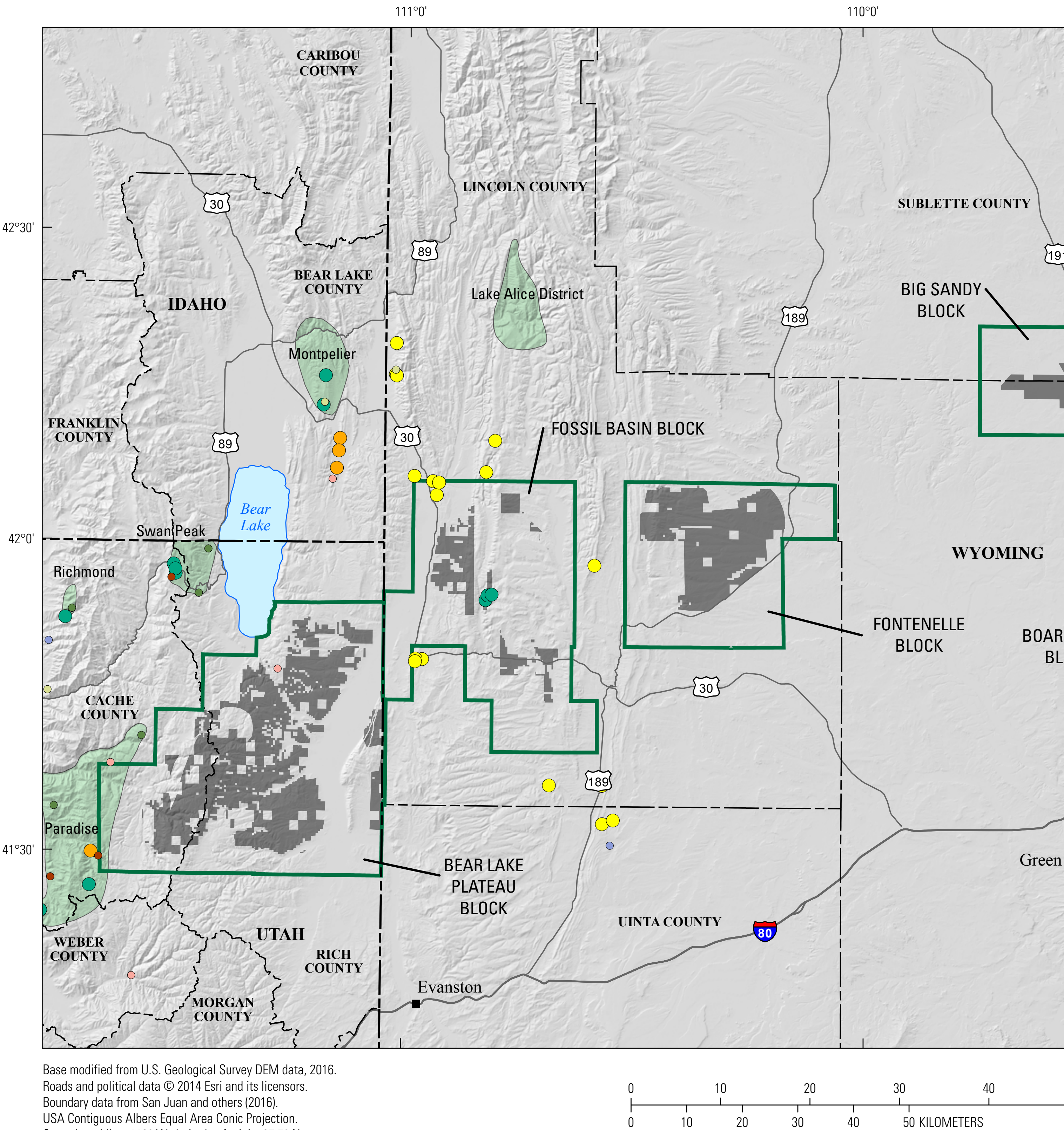



**Figure 21.** Map showing 43 CFR 3809 surface-management authorizations for locatable commodities in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey.

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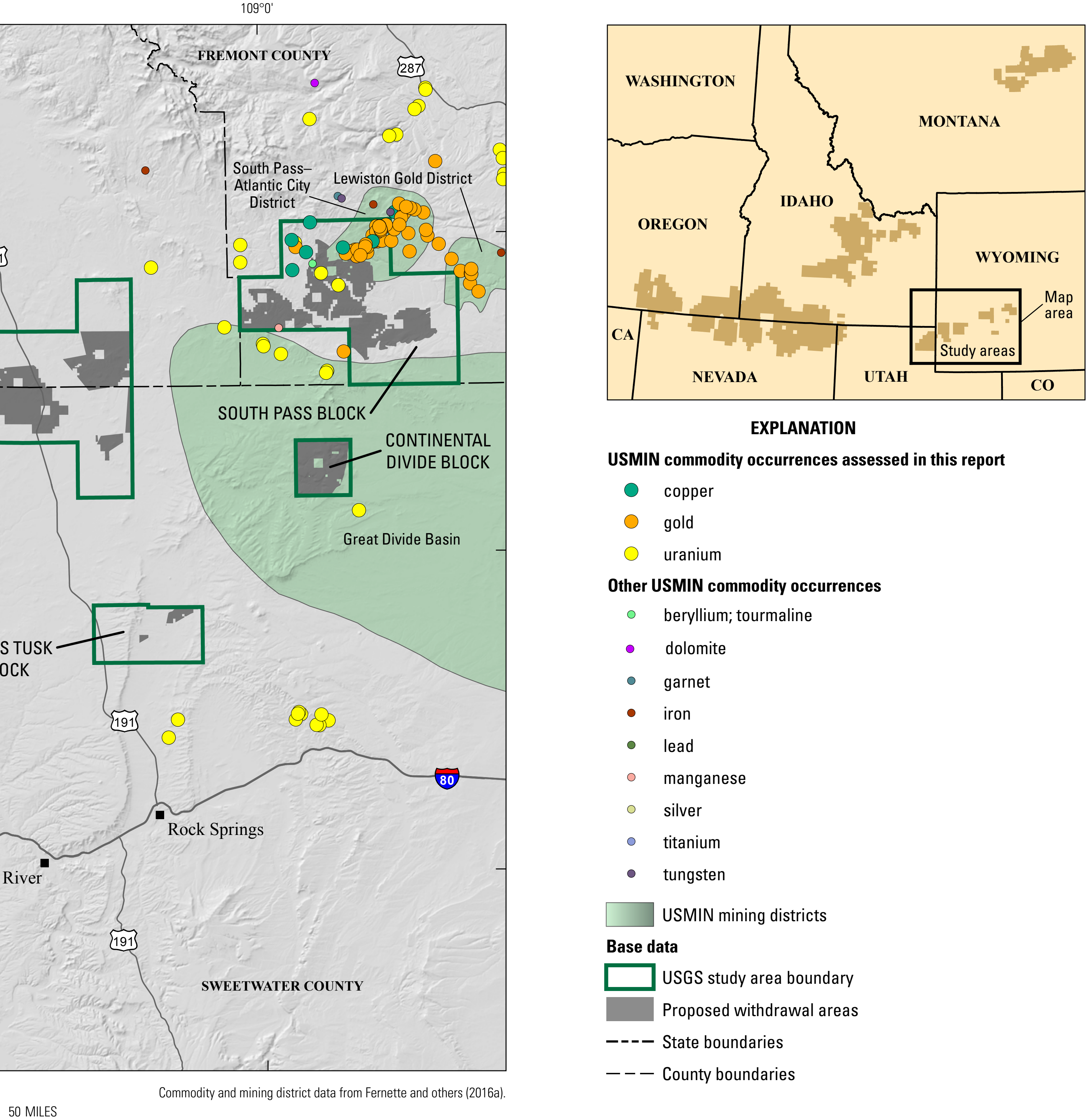



**Figure 22.** Map showing mineral deposits, mines, and important exploration prospects for locatable commodities in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming, and Utah. USMIN, U.S. Geological Survey (USGS) Mineral Deposit Database.

## Hydrothermal-Metamorphic Mineral System

Mineral deposits that form from hydrothermal fluids generated by thermal events associated with major fault zones occur in orogens formed by large-scale processes related to convergence of tectonic plates (Hageman and Cassidy, 2000). The fault zones may cut regionally metamorphosed rocks of all ages, can be as much as several kilometers wide and more than 100 km long, and are nearly vertical. Such deposits are most commonly enriched in gold with lesser silver, and some are also enriched in copper, lead, tungsten, and zinc.

### Orogenic Low-Sulfide Gold-Quartz Veins (Orogenic Gold Veins)

#### Mineral Description

In deposits of this type, gold mineralization is primarily found in hydrothermal quartz veins in shear zones that occur near major fault zones in metamorphic rocks. Gold deposition occurred in and near fault zones at depths ranging from 3 to 20 km from fluids that were apparently generated from prograde metamorphic devolatilization reactions (reactions that give off water ($H_2O$), carbon dioxide ($CO_2$), methane ($CH_4$), and possibly other compounds, as heat and pressure are increased) in eugeosynclinal sedimentary and volcanic rock sequences. In such fluids, the gold is probably complexed with bisulfide anions, and the metal precipitates where the complex is destabilized, probably by the precipitation of sulfides. In some systems of this kind, mineralization in the veins can be traced to more than 2 km in depth. The veins are mainly composed of quartz (silicon dioxide, $SiO_2$), with less abundant carbonate minerals, such as ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$), siderite ($FeCO_3$), and calcite ($CaCO_3$). Pyrite ($FeS_2$) and arsenopyrite (FeAsS) constitute less than 5 percent of the veins. The main ore mineral in most deposits is native gold. Orogenic low-sulfide gold-quartz veins are found in continental metamorphic belts of almost every geologic age, from Archean to Miocene. Hammarstrom and Zientek (2016) provide an overview of the methodology, and appendix 3 in Day and others (2016) provides a synopsis of the orogenic low-sulfide gold-quartz veins deposit model.

#### Geology and Occurrence in the Study Area

Orogenic low-sulfide gold-quartz veins have been known within the South Pass block of the Southwestern and South-Central Wyoming study area since 1864, when soldiers from Fort Bridger discovered a lode north of present day Atlantic City, Wyoming, and located a claim on it, naming it the Buckeye lode (Coutant, 1899, p. 639–640). In the next summer, 1865, a second group of Fort Bridger soldiers was in the area, and a soldier named Tom Ryan discovered the gold-bearing Carissa lode (Layman, 2012). In spring of 1867, the H.S. Reedall party of 5 to 10 men left Salt Lake City with intent to locate Ryan's discovery, claim it, and work it. They located the "Cariso" lode and established the Shoshonie Mining District. Within a year they had recovered $15,000 in gold (about 750 troy oz) using only hand methods of mining and recovery. In the summer of 1867, Lewis Robison, a mountain man, arrived in Salt Lake City carrying 40 oz of gold reportedly recovered in 2 days in the South Pass-Atlantic City area (Bagley, 2011). The results of Robison's and the Reedall party's efforts set off a gold rush to South Pass City and Atlantic City over the next couple of years. By 1869, there were more than 300 structures and 1,900 people in South Pass City, but a bust soon followed and the 1880 census registered fewer than 200 people. However, like many of the districts that were discovered in the second half of the 19th century, the South Pass-Atlantic City district has seen renewed activity in nearly every time of high gold prices, a trend that continued into the 1990s.

The gold-bearing quartz veins in shear zones mined in the South Pass-Atlantic City district are hosted by, and deformed within, shear zones, most of which cut the Miners Delight Formation (fig. 23), a sequence of metagraywacke intruded by sills and fewer dikes of metadacite and orthoamphibolite (metadiabase). The Miners Delight apparently overlies the Roundtop Mountain Greenstone, which itself overlies the Goldman Meadows Formation, and the informal Diamond Springs formation, in order. The Roundtop Mountain Greenstone consists mostly of basalt, some of it pillowed, whereas the Diamond Springs consists of mostly serpentinized ultramafic volcanic rocks. The Goldman Meadows is composed of pelitic schist that alternates with magnetite facies banded iron formation, the rock type that was mined for 20 years by U.S. Steel in their Atlantic City open pit, about three miles north of Atlantic City. All of the rocks in the metasedimentary and metavolcanic package are tightly folded into a large syncline with many smaller-scale steep folds enclosed in it: bedding dips steeply inward from the South Pass-Atlantic City district on the northwest side, and from the Lewiston district on the southeast side. In general, the most productive shear zones strike and dip nearly parallel with bedding and foliation, most dipping near-vertical. However, in the middle of the syncline, the Miners Delight Formation contains only sparse shear zones and essentially no evidence of gold mineralization. Productive shear zones are found preferentially along and within metadacite and metadiabase sills, and those dikes and sills are nearly absent from the center of the syncline. Preference of the gold mineralization for shear zones, rather than thick, undeformed quartz veins, was observed by Hausel (1991, p. 32 and p. 40). Relatively thick and continuous quartz veins, at the Alpine and Tornado Mines in the South Pass-Atlantic City district and the Lone Pine Mine in the Lewiston district, have had only small production whereas nearby shear zones are among the most successful mines of the districts, including the Franklin, Carissa, and Miners Delight Mines (fig. 24). Another 10 mapped veins of massive quartz (Hausel, 1991) have no recorded production.

Both sides of the syncline were later intruded by granitic batholiths. The Louis Lake granodiorite intrudes on the northwest, and an unnamed granodiorite intrudes southeast of

Lewiston. The youngest Precambrian magmatism in the area occurs west of South Pass City where granite dikes and plugs, accompanied by numerous granitic pegmatites, intruded the Miners Delight Formation (Bayley and others, 1973).

The productive shear zones of the South Pass-Atlantic City district have envelopes of altered (sericitized) rock that are typically narrow, rarely thicker than a couple of meters, but have impressively thick zones of gold mineralization at a few places (for example, Hausel, 1991, p. 45). The shear zones and veins contain the expected carbonate gangue minerals along with quartz, arsenopyrite, and pyrite. A few of the veins and shear zones also contain up to several percent chalcopyrite (copper iron sulfide, $CuFeS_2$) with at least two of the copper-rich veins occurring near the contacts of the supracrustal rocks with the Louis Lake granodiorite (the Anderson Ridge and Tornado Mines; fig. 24).

Like in other gold districts of this type, fluid inclusions in quartz homogenize at around 275 °C, which, when corrected for the pressure at the time of trapping, is about 350 °C on the basis of their carbon dioxide and methane contents. The fluids are relatively dilute, averaging about 12.24 NaCl equivalent weight percent, and contain high $CO_2$ concentrations and some methane. The average bulk fluid composition was 83.09 mole percent water, 16.15 mole percent $CO_2$, and 3.46 mole percent NaCl. The fluids and the gold are believed to have been released from the sedimentary and volcanic rocks during high-grade metamorphism at depth (McGowan, 1990).

### Exploration and Mining Activity

The South Pass-Atlantic City district had some 33 patented lode gold claims or groups of claims, many of those patented more than 100 years ago (Bureau of Land Management, 2016). Mining activity has continued sporadically even to the present day. In the part of the district within the South Pass block (8 of the district's 14 total sections) there are 38 active lode claims (mostly unpatented) and 7 active placer claims. There are no known pending actions regarding lode gold mining in the eight sections of the district within the South Pass block. (There are two authorized surface management plans for lode gold operations in those same eight sections within the district.) Examination of a Bureau of Land Management map from 1972 (Layman, 2012) indicates that, at that time, around 40 patented lode claims, were still in private ownership in the district. The Lewiston district has a similar history; it had 11 patented lode claims or groups of claims. Historically, lode gold mining has produced in excess of 224,823 troy oz of gold from South Pass-Atlantic City district and more than 21,000 troy oz of gold from the Lewiston district (Hausel, 1991, table 1, p. 30–31.) The largest producing mines in South Pass-Atlantic City district, listed in order of total ounces produced, were the Miners Delight (60,000 troy oz), Carissa, Caribou, Soules and Perkins, and Garfield (Buckeye) (21,000 troy oz) (fig. 24). (Note that the Miners Delight Mine is well outside the study area and is therefore not included in table 2.)

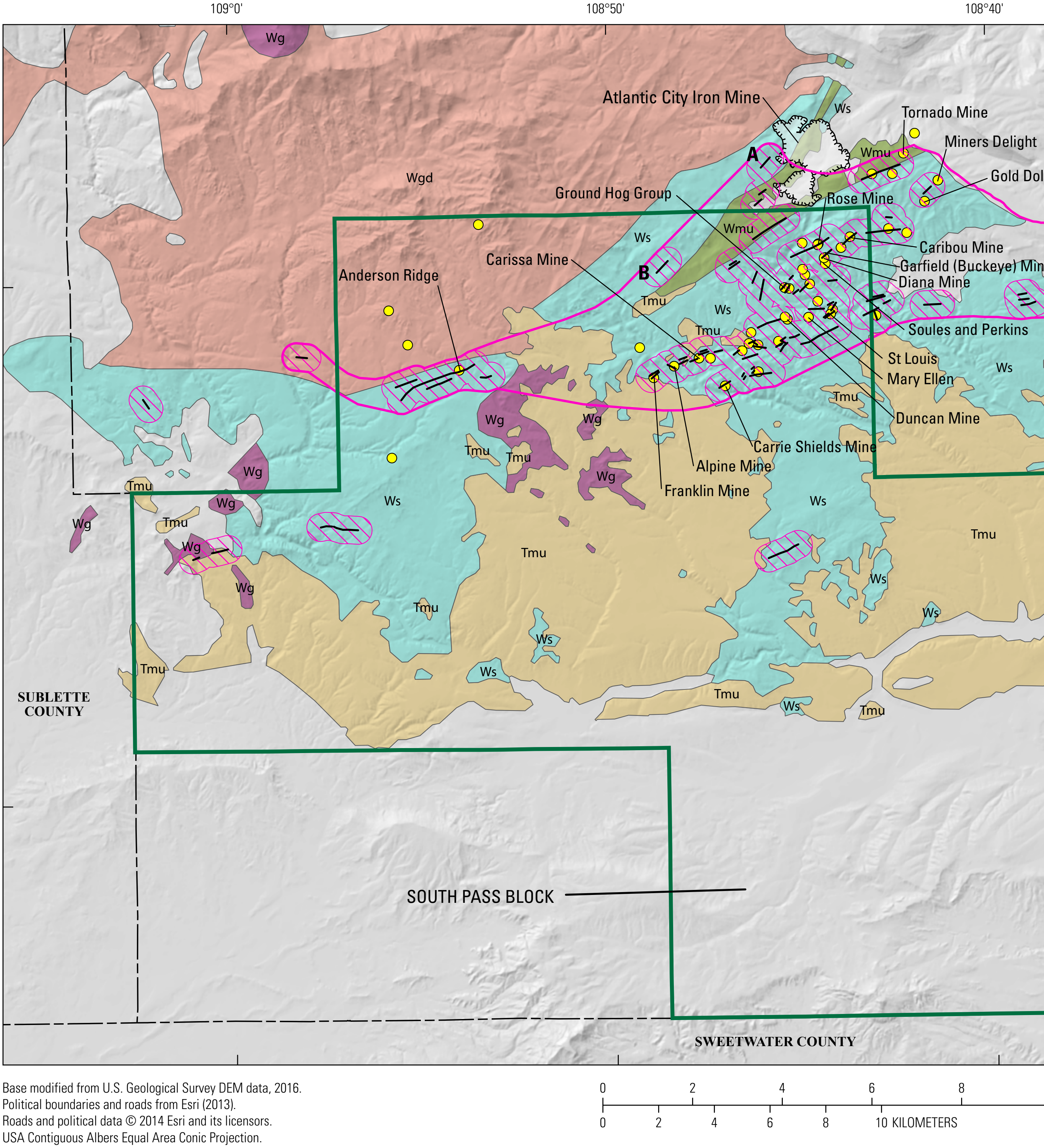
A notable recent cycle of exploration activity took place in the South Pass-Atlantic City district from the mid-1970s into the 1990s, spurred when the U.S. Government abandoned the gold standard in 1971, which released the price of gold from a fixed $35 per troy oz to rise to its free-market value. In the decade following, the price of gold rose briefly to more than $1,800 per troy oz before settling slowly to around $1,300 per troy oz, near where it remains today.

Anaconda Copper was among the first companies to reexamine South Pass-Atlantic City district after the gold price was released, and they drilled several holes near the Carissa mine in 1974 (Hausel, 1991. p. 45). One hole intersected the Carissa shear zone at 198 to 213 m (650 to 700 ft) depth, where the zone was 4.9 m (16.1 ft) thick grading 4.4 grams per metric ton (g/t) of gold (Hausel, 1991. p. 45). Additional mineralized rock was encountered at depths between 213 and 284 m (700 and 930 ft) below surface. Carissa underground workings consist of five levels. The primary shaft reaches the 4th level at 107 m (350 ft) below the surface and a winze connects with the 5th level at 122 m (400 ft) depth. The four upper levels support stopes; the nearly 700 m (2,300 ft) of drifts in the old workings extend as much as 232 m (760 ft) along strike. There appears to be considerable rock of good grade between 107 and 284 m (350 and 930 ft) below surface along the shear zone, which averages 1.8 m (6 ft) wide at the surface (Hausel, 1991). Hausel (1989) showed that a zone 30 m (97 ft)-wide containing the shear zone is mineralized to 0.8 g/t (0.0223 oz per short ton). Even ignoring the deeper mineralization, there is considerable unmined rock of good grade within the first four levels. In the second half of the 1980s into the 1990s, Consolidated McKinney Resources, a Canadian junior mining company from Vancouver, explored the Carissa and drilled eight holes. Reporting to Consolidated McKinney, de Quadros (1989) stated that H.S. MacFarlane with Carissa Gold (who operated the mine between October, 1949, and January 1955; Layman, 2012), calculated that remaining resources from levels 1 through 4 totaled 229,500 metric tons at 13.5 g/t at a 9.34 g/t cutoff (252,400 short tons at 0.432 troy oz per short ton at a cutoff grade of 0.274 troy oz per short ton) (Hausel, 1991).

In 1967, the State of Wyoming purchased all of the property and structures of South Pass City and designated them as an official state historic site. In 2003, the State of Wyoming bought the Carissa Mine, mill, and patented claims, adding them to the South Pass City Historic Site (Layman, 2012). The State has since cleaned out and restored the mill building and rebuilt an ore pass platform from the head of the shaft into the mill. Both are now suitable for tourists to visit.

### Potential for Occurrence

Tracts for undiscovered orogenic low-sulfide gold-quartz veins in and near the South Pass-Atlantic City district and the Lewiston district are based on the most important mappable feature of the known deposits, the mineralized shear zones. Hausel's (1991) geologic map at 1:48,000-scale was used to delineate the mineralized zones. Each of the shear zones,

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Political boundaries and roads from Esri (2013).
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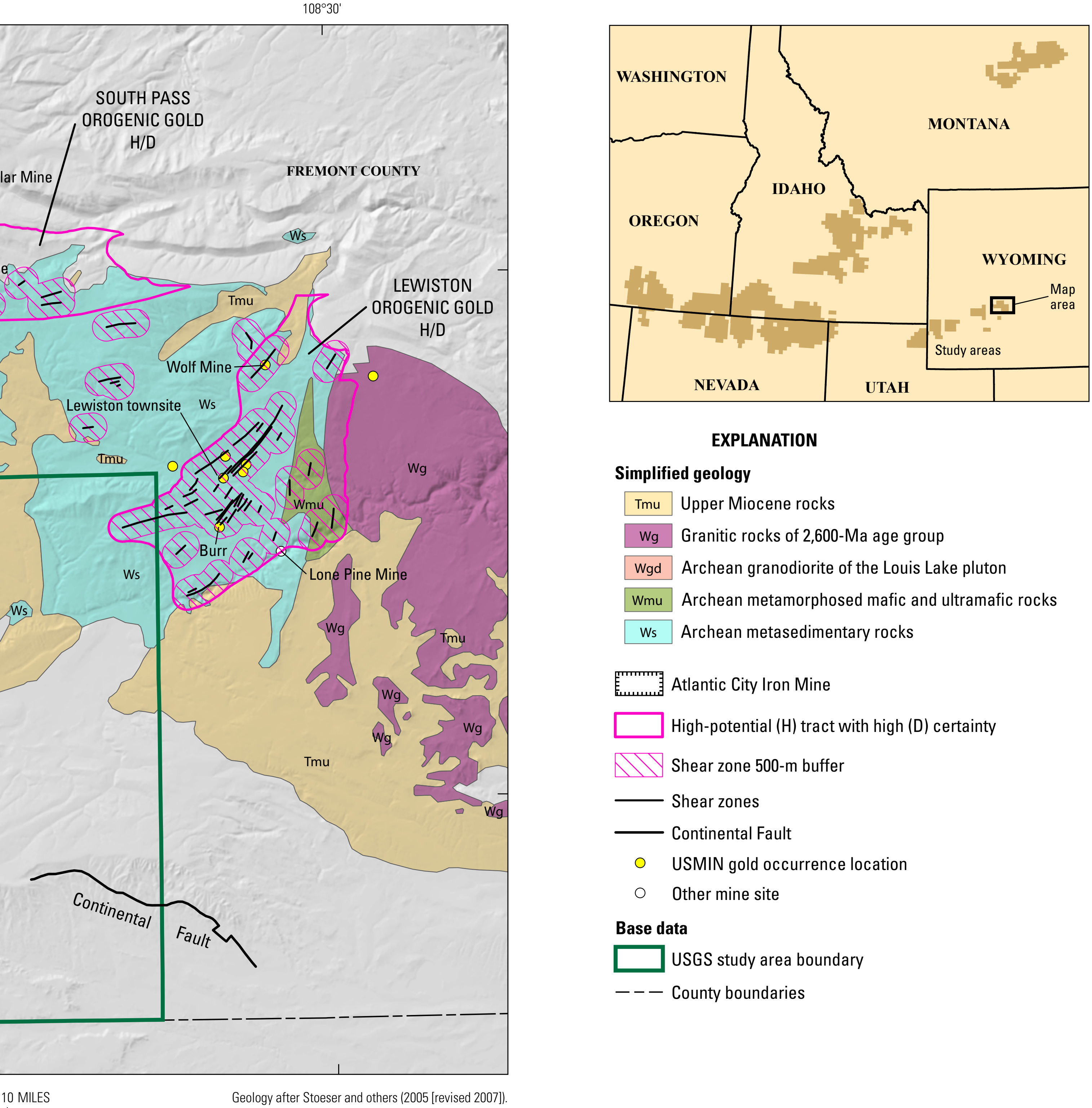
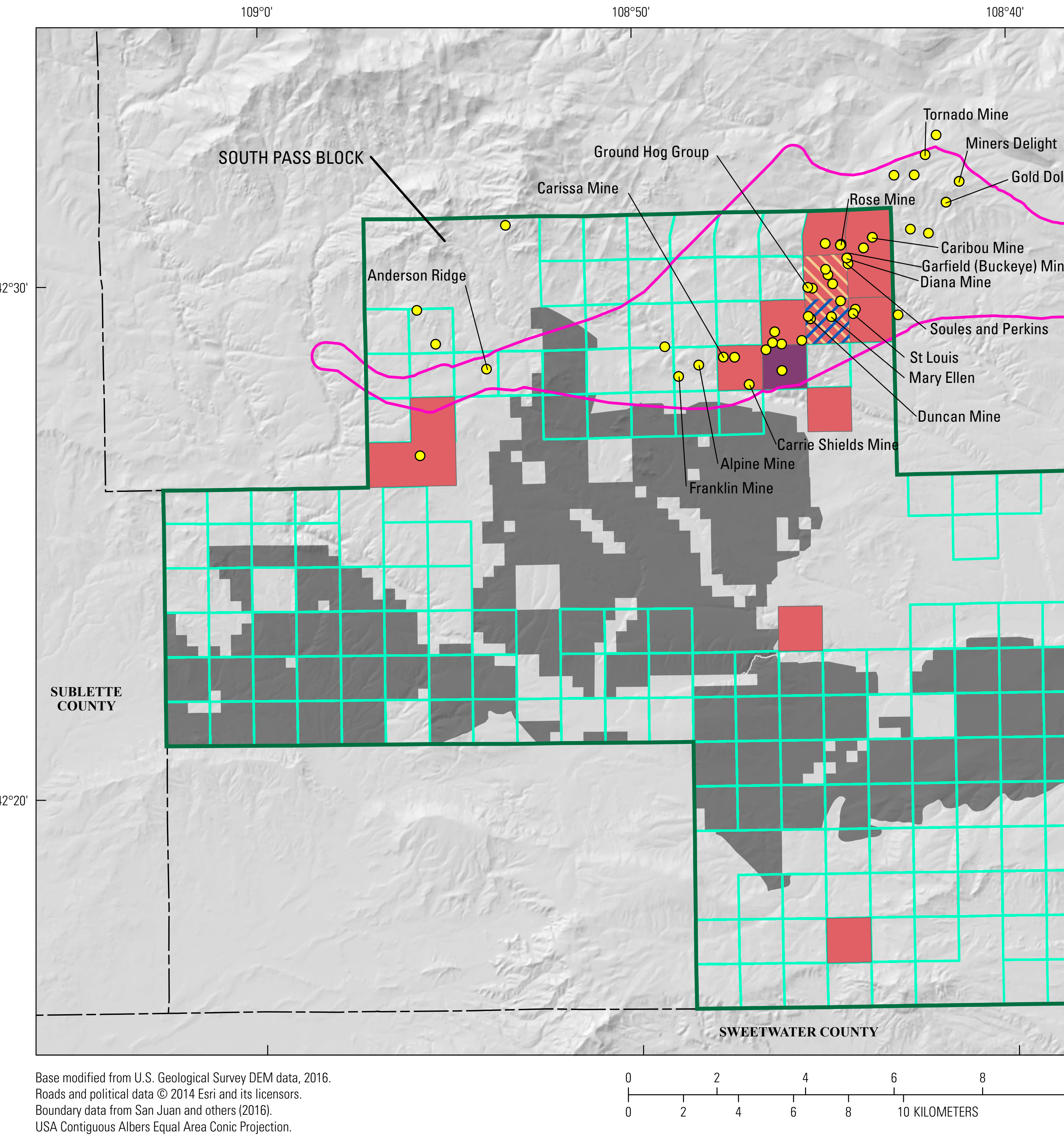



Geology after Stoeser and others (2005 [revised 2007]).
Shear zones and Atlantic City Mine after Hausel (1991).
Fault data from Sutherland and Hausel (2006).
USMIN gold locations from Fernette and others (2016).

**Figure 23.** Map showing the geology of the South Pass block, Southwestern and South-Central Wyoming study area, Wyoming. USMIN, U.S. Geological Survey (USGS) Mineral Deposit Database. Ma, mega-annum or millions of years ago; m, meters.

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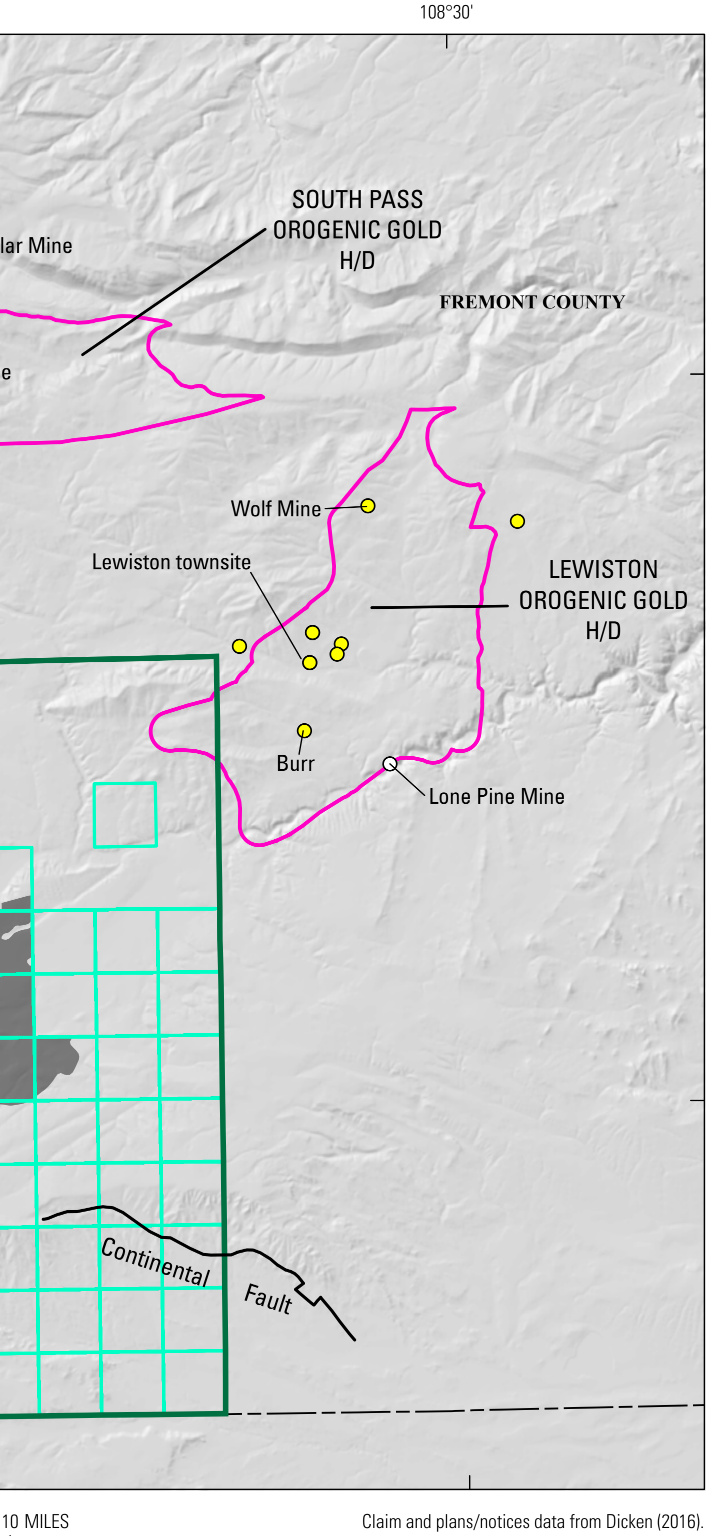
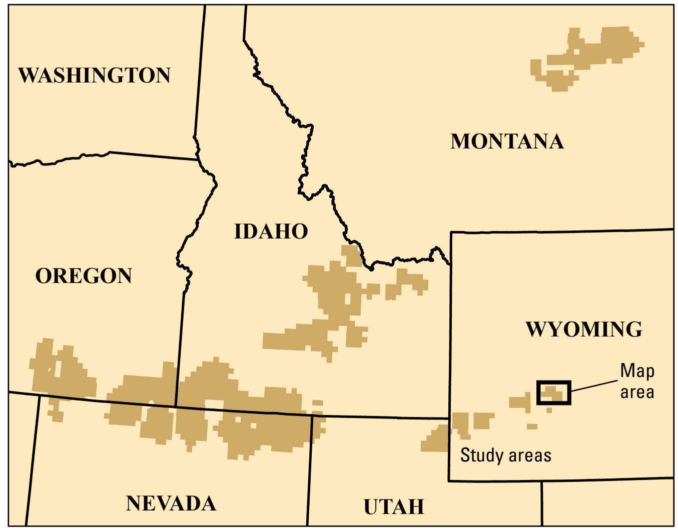



Claim and plans/notices data from Dicken (2016).
Fault data from Sutherland and Hausel (2006).
USMIN gold locations from Fernette and others (2016).

**EXPLANATION**

**Townships containing BLM mining plans and notices**

Authorized surface management plan for gold lode

Pending surface management plan for gold

**Townships containing BLM mining claims**

Active lode claim

Closed tunnel site

Closed lode claim

**Assessment tract types – low-sulfide orogenic gold veins**

High-potential (H) tract with high (D) certainty

Fault

USMIN gold locations

Other mine site

**Base Data**

USGS study area boundary

Proposed withdrawal areas

County boundaries

**Figure 24.** Map showing location of orogenic-gold mines and claims, with geology and resource potential tracts, in the South Pass block, Southwestern and South-Central Wyoming study area, Wyoming. BLM, Bureau of Land Management; USMIN, U.S. Geological Survey (USGS) Mineral Deposit Database.

which in this district are zones of high strain that range to as large as 5 km long and 10 m wide, were buffered by 500 m on the sides and ends (fig. 23). All of the mineralized shear zones and their buffer zones were then enclosed in smoothly curving boundaries. Indications of mineralizing processes on the shear zones were any kind of exploration or mining activity as symbolized by Hausel (1991), including shafts, adits, trenches, and prospect pits. Five hundred meter buffer zones were chosen after attempting the same exercise with one-mile and one-kilometer buffers. The larger buffers included almost the entire syncline. Hausel's mapping was at the same detail, across the central area of the syncline, yet he recorded almost no indication of any gold-exploration or mining across the central part of the syncline. Using the smaller buffer zones, there are eight shear zones excluded from the tract, all eight mapped near the middle of the syncline, and seven of those have no signs of mining activity (Hausel, 1991, plate 1). Furthermore, three of the eight cut at high angles across the layering in the Miners Delight Formation, unlike nearly all of the mineralized shears which are parallel to layering. Last, none of the eight shears near the middle of the syncline are associated with any metadacite or metadiabase sills or dikes. Of the 106 mapped shear zones or veins, only 17 are not also within 500 m of a mapped metadacite or metadiabase sill or dike, including those eight shear zones excluded from the smooth outline.

The tract ends on the northeast where the Cambrian Flathead Sandstone contact is reached, and, northeastward from there, the Flathead rocks overlie the favorable Archean rocks. In fact, however, resource potential actually continues beneath the Flathead Sandstone and other rocks to the northeast. However, the covered Archean rocks with mineral resource potential for orogenic gold-quartz veins are, in that direction, farther and farther away from the boundaries of the proposed withdrawal area at South Pass.

The tract containing all the mineralized shear zones of the South Pass-Atlantic City district is labeled South Pass (fig. 25). The corresponding tract that covers the Lewiston district is labeled Lewiston. These tracts are rated with high (H) potential at certainty level D. That there is remaining potential in the district is amply proven by Anaconda's drilling at the Carissa mine where the mineralized shear zone was found to a depth below surface of 283 m (930 ft). It is expected that other of the district's near-vertical mineralized shear zones also continue to considerable depth, and to our knowledge, none of the others has been drill tested. Additional potential in the South Pass Orogenic Gold tract lies in areas where the Archean rocks are covered by Tertiary sediments between the Franklin and Anderson Ridge Mines (fig. 23). No less than 2.4 km of the total distance of 7.2 km is covered by the Tertiary and Quaternary sediments, and the area between extends subparallel to the elongation direction of shear zones in areas of outcrop both to the east and west. Drilling targets might be established in covered areas using combinations of magnetic surveys to estimate depth to the top of Precambrian crystalline rocks and electromagnetic or induced polarization surveys to identify electrically conductive rock types. Though this type of deposit does not have a lot of sulfides, even a small amount should still contrast with the probably high-resistivity Miners Delight greywacke and late granites.

No tract is drawn for the Archean rocks of the center of the syncline (either where they are exposed or where they are covered by Tertiary sediments). There appears to be no indication of gold mineralizing processes through the middle of the syncline, although it is possible that geologic conditions like those at the northwest and southeast boundaries of the syncline might be present as well near the bottom boundary of the syncline, at great depth.

The Lewiston Shear Zone Extension tract extends to the southwest from the southern end of the Lewiston Orogenic Gold tract. The tract is delineated by extending from the southernmost of the mapped shear zones of the Lewiston district by a distance equal to the largest gap between collinear shear zones mapped anywhere in either the Lewiston or South Pass-Atlantic City district. That largest gap distance is interpreted as a measure within which prospectivity still exists—the measure derived from geometry of shear zones in the mining district, itself. The largest gap between the ends of mapped collinear shears is 4,734 m (labeled A and B on fig. 23). Therefore, 7,734-m extensions were added to the southernmost shear zones in the Lewiston Orogenic Gold tract and buffered by 500 m. The southwest end of the tract is constructed by connecting the end of the buffer zones by straight lines from one shear zone extension end to the next. The result, overall, is that the tract is shaped like a segment of a fan (fig. 25).

Because the potential is considered to be high in the Lewiston Orogenic Gold tract to the north, the potential in the continuation to the south in the Lewiston Shear Zone Extension tract is also considered high (H), yet the certainty is considered to be lower than the tract to the north and east and is rated at level B because there is no direct evidence of mineralized rock in the parts of the tract where the Precambrian rocks are under Tertiary rocks.

An additional tract, the Lewiston Extension Under Tertiary Cover tract, extends permissive rocks farther to the southwest beneath younger cover rocks. In USGS mineral resource assessments, mineral potential is typically estimated to a depth of 1 km. The Archean Miners Delight Formation hosts the orogenic low-sulfide gold-quartz vein deposit-type in the Lewiston area. North of the Sweetwater River (fig. 3) the top of the gold-bearing Archean basement gently dips to the south and is covered by the northern extent of a vast expanse of Tertiary sediment, thus burying the rocks that have potential for orogenic low-sulfide gold-quartz vein deposits. The potential for the occurrence of orogenic low-sulfide gold-quartz veins clearly continues south and southwest of the known Lewiston district under Tertiary (and Quaternary) cover. In the Willow Creek drainage area the Tertiary/Archean erosional surface dips gently to the south from 1 to 6 degrees, and that surface has a rugged paleotopography developed on it with local relief of several hundred feet. Nonetheless, assuming an overall gentle southward regional dip of 5 degrees, the southward extent to which the Archean rocks would be buried to a depth of 1 km or less would be over 11.5 km. Thus the tract, entirely beneath Tertiary cover, extends from the contact of Tertiary sediments onto Archean rocks and continues for 11.5 km in the direction of the mapped shear zones to the north or northeast. The 500-m buffers on the sides of the outermost shear zones are continued south or southwestward. Again, a southern or southwestern end for the extension is provided by connecting the buffered end of the shear zone extensions with straight lines, producing a tract with a shape like another segment of a fan, this one opened wider than the shear zone extension tract. The tract thus extends 11.5 km from the edge of exposed Precambrian rocks near Lewiston.

The southern extent of the Lewiston Extension Under Tertiary Cover tract is terminated at the Continental Fault, although it is possible that mineralization could extend beyond the fault (fig. 25). The Continental Fault is a normal fault upthrown on the south, such that the Archean/Tertiary contact would be displaced to higher elevation on the south side of the fault. As a result, Archean rocks permissive for undiscovered orogenic low-sulfide gold-quartz vein deposits could extend on the south side of the Continental Fault.

The extent and location of Archean rocks south of the fault, however, is highly uncertain. There is an intimate relationship between the location of the Continental Fault and the location of the underlying Wind River thrust (Berg, 1983). According to seismic stratigraphy and petroleum exploration drill holes, the Continental Fault nearly overlies the top of the sharp edge of the wedge of Precambrian rock that was thrust southwestward late in the Laramide orogeny (Berg, 1983). In areas to the northwest of the South Pass proposed withdrawal area, the vertically projected thrust edge—the sharp edge of the wedge of Precambrian rock projected vertically to the land surface—lies 1.6 km or less to the southwest from the trace of the Continental Fault locally, and at other places, the Continental Fault lies 1.6 km or less to the southwest of the vertically project thrust edge. The thrust edge marks the place where the Archean/Tertiary contact would fall dramatically in elevation from perhaps 1,830 to 1,980 m in elevation (at the leading edge of the hanging wall), to more than 6,100 m below sea level vertically below on the footwall block (Berg, 1983, figure 4, p. 260). Thus, locally, the Lewiston Extension Under Tertiary Cover tract would continue to the south of the Continental Fault, but at other places, that surface will have dropped very abruptly to more than 20 km (12 mi) below the surface before reaching the Continental Fault. Without both seismic surveys and drill-hole information that provides ground truth for the seismic results, the location of the vertical projection of the thrust edge cannot be accurately located, and we cannot know where the tract should end before the Continental Fault (at the vertical projection of the edge of the wedge of thrusted Precambrian rock) versus where a relatively small amount of additional land should be added to the tract south of the Continental Fault. Therefore, we chose to end the Lewiston Extension Under Tertiary Cover tract at the Continental Fault, a place that is typically marked on the ground by sharp changes in topography and rock types (figs. 23 and 25).

The Lewiston Extension Under Tertiary Cover tract, either at the start of cover over the prospective Precambrian rocks or where the Precambrian rocks are covered by substantial thicknesses of Tertiary rock, cannot, with any certainty, be asserted to contain gold-bearing shear zones. Continuity of the Archean metasedimentary and metavolcanic host rocks is reasonably assured, but not the continuity of the mineralized shear zones; therefore, the tract is rated with moderate (M) potential at a level of certainty of A. A geologic environment for these Precambrian rocks (metamorphosed eugeosynclinal package with metavolcanics, metapelites, and metagraywacke) is known to potentially host orogenic low-sulfide gold-quartz veins, but no more is known except that gold-bearing shear zones are present several kilometers to the north and northeast. Without further evidence, the distance is too great to assume continuity of any single shear zone or even a section containing shear zones at all, so high potential is not indicated. Geophysical surveys indicating rock with low resistivity in the Precambrian wedge might be taken as indication of sulfide-bearing shear zones, but no "electrical" geophysical surveys exist for the tract area. With no exposure of any kind and no geophysical surveys, the available data are insufficient and cannot be considered as evidence either for or against resource potential for orogenic low-sulfide gold-quartz veins.

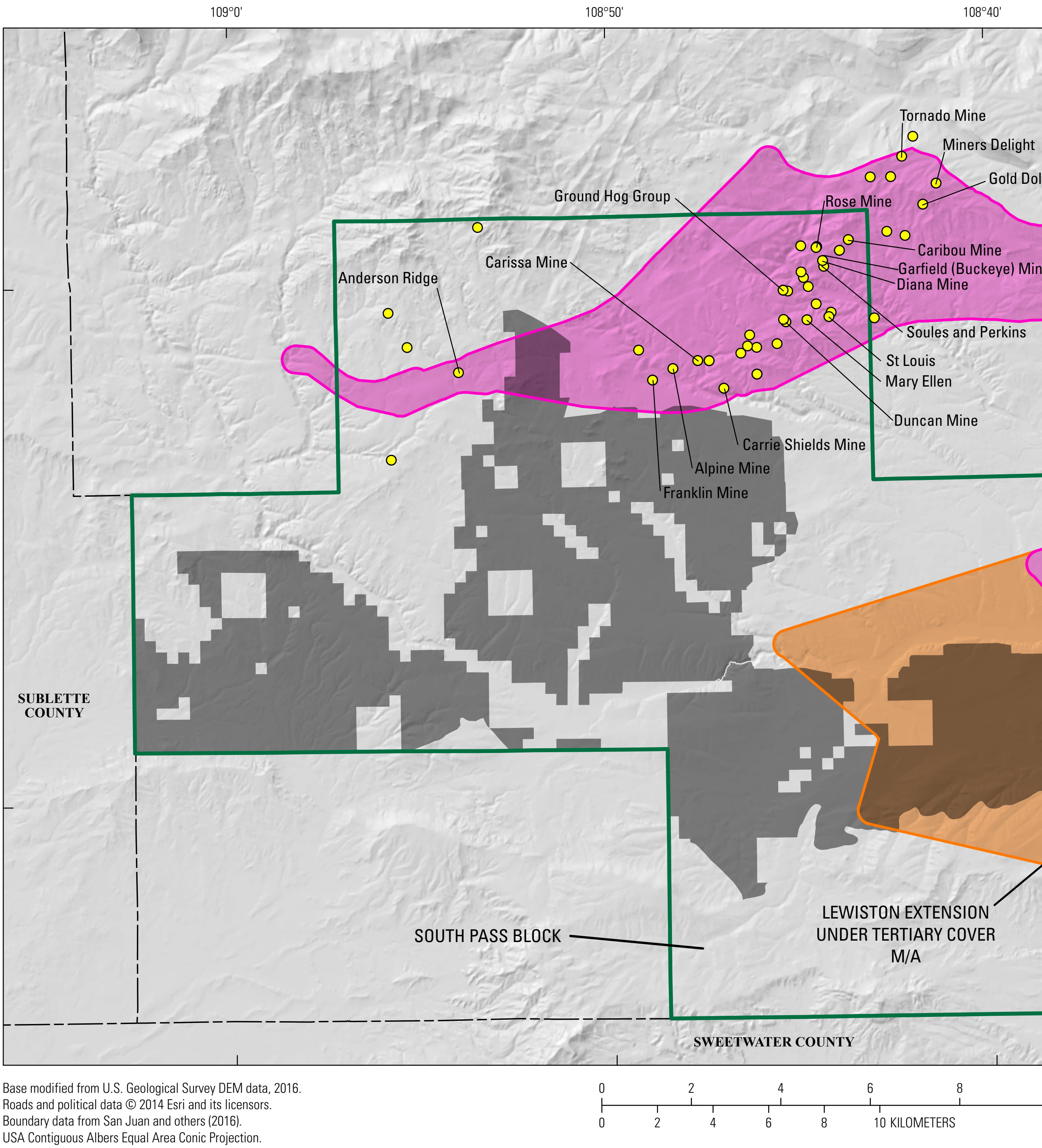
### Economic Analysis

Gold deposits on the margins of the study area have been economically viable in the past and may be so again in the future in the tracts delineated as South Pass Orogenic Gold and Lewiston Orogenic Gold. Deposits in the Lewiston Shear Zone Extension tract would be at depth, and thus more expensive to locate and develop. Any deposits in the Lewiston Extension Under Tertiary Cover tract are purely speculative at this time.

Discussion of where gold is being produced in the Western United States can be found in Bleiwas (2016). None of the current gold production from Utah is within the study area, and there is currently no gold production in Wyoming.

## Sedimentary Mineral System

A variety of mineral deposits are formed within sedimentary rocks by processes themselves restricted to the enclosing sedimentary basin. Processes of diagenesis, using only water that is trapped with the sediments, can result in the conversion of volcanic ash into bentonite clay or ashy sediments into valuable zeolite minerals. Epigenetic deposits of base metals with or without barite can be deposited by mixing groundwaters that permeate from distances of tens or hundreds of miles away with the connate water trapped with the original sediment. Alternatively, far-traveled groundwater can deposit zinc, lead, barite, and silver by discharging into the seawater immediately above the seafloor where it mixes and reacts with the seawater. Sandstone-hosted deposits of uranium, vanadium, and copper can be precipitated from waters recharging




Base modified from U.S. Geological Survey DEM data, 2016.
Roads and political data © 2014 Esri and its licensors.
Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

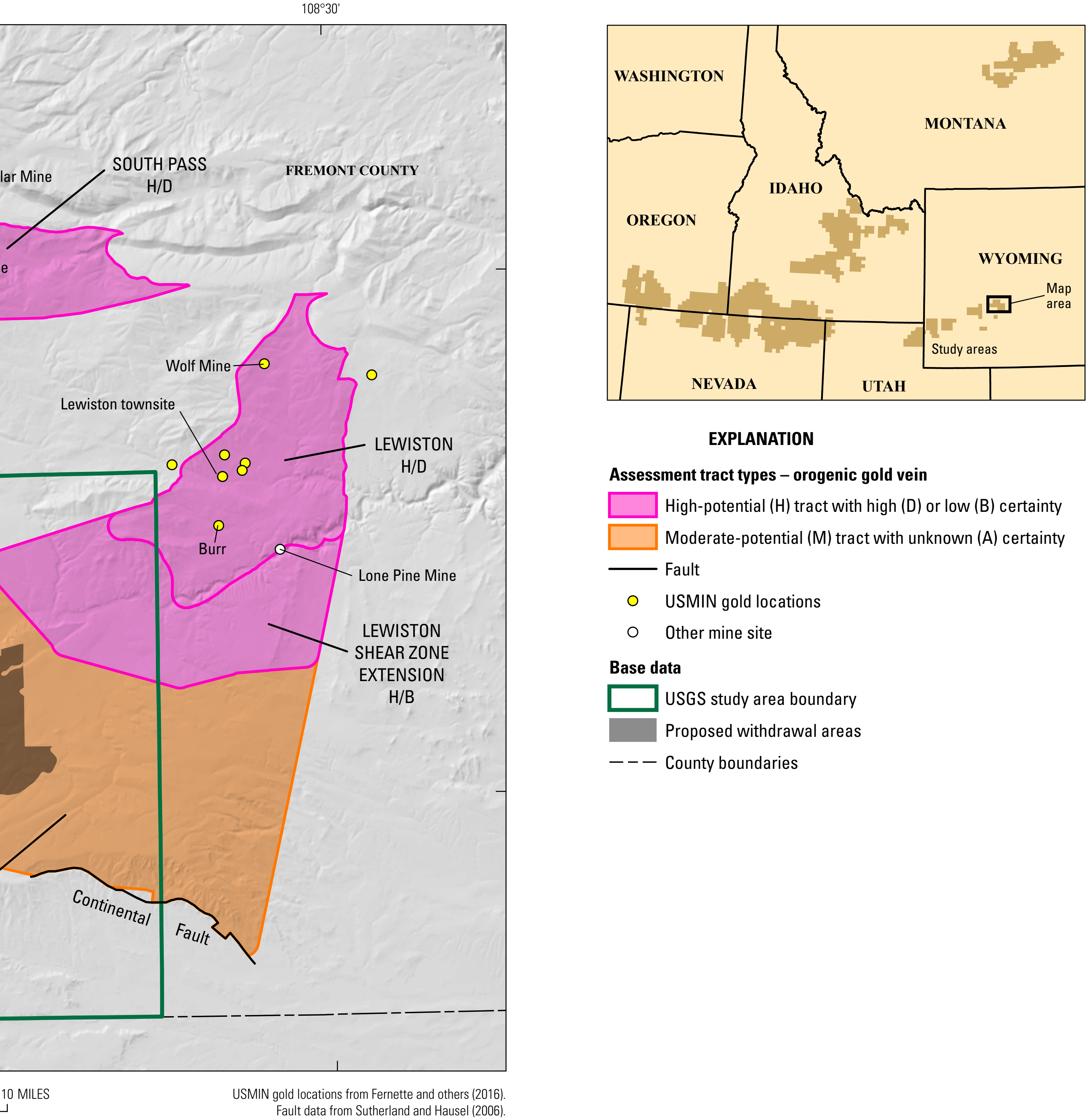



**Figure 25.** Map showing the mineral-potential tracts for orogenic low-sulfide gold veins in the South Pass block, Southwestern and South-Central Wyoming study area, Wyoming. USMIN, U.S. Geological Survey (USGS) Mineral Deposit Database.

from the surface, where those waters mix and react with the connate water and with constituents of the diagenetically changed sandstone. A far-traveled epigenetic groundwater can precipitate copper and possibly silver or cobalt by discharging from a red-bed package into carbonaceous rocks or into a sour gas reservoir.

## Sediment-Hosted Stratabound Copper Deposits

### Mineral Description

Sediment-hosted stratabound copper deposits consist of fine-grained, copper- and copper-iron-sulfide minerals that form stratabound to stratiform disseminations in siliciclastic or dolomitic sedimentary rocks. Chalcocite ($Cu_2S$) and bornite ($Cu_5FeS_4$) typically cement the host rocks and replace certain detrital grains and earlier cements. Sulfide minerals occur less commonly as veinlets. The concentration of sulfide minerals generally conforms closely with stratification of the host rocks, but, in detail, may cross the stratification. Deposits are characterized by zoning of ore minerals laterally along and across bedding from pyrite to chalcopyrite to bornite to chalcocite to hematite ($Fe_2O_3$) (Hayes and others, 2015; see appendix 3 in Day and others, 2016). Fringes of ore bodies distal from the source of ore solutions may contain sphalerite ((Zn,Fe)S), galena (PbS), and pyrite coexisting with chalcopyrite and may grade farther yet from the source to rock, whose only sulfide is pyrite. The gentle cross-through beds of epigenetic zones of hematite (with $Fe^{3+}$) grading to copper sulfides grading across the zonation to pyrite (with $Fe^{2+}$) are evidence that oxidation/reduction processes were involved in ore precipitation.

Sediment-hosted stratabound copper deposits are formed in sedimentary basins that contain relatively thick (>300 m and commonly >1 km) successions of red (hematitic) clastic sedimentary rocks with or without evaporites, or in basins that have thick subaerially erupted (continental) basalt sequences. Based on ore and gangue mineral zoning and alteration, mineral paragenesis, fluid inclusion studies, and stable isotope geochemistry, the metal-bearing fluids were low temperature (75–220 °C), hematite stable (oxidized), sulfate- and chloride-rich, subsurface brines generated during compaction and lithification of the sediments in the basin (Zientek and others, 2013a; Hayes and others, 2015). The primary cause of base-metal sulfide precipitation is reaction of the ore fluid (the cupriferous brine) with rocks or fluids that either provide sulfide, or form sulfide from ore fluid sulfate by reduction (Hayes and others, 2015).

Three subtypes of sediment-hosted stratabound copper deposits are recognized based on the processes responsible for precipitation of copper sulfides. In the reduced facies subtype, amorphous solid carbonaceous material in dark gray to black shale or siltstone serves as the reductant of ore fluid sulfate to form sulfide. Resulting deposits are sheet-like, following the beds of organic-rich shale or siltstone. Though they may be just a few meters to about 10 m thick, reduced facies deposits have areas commonly in the tens of square kilometers, and in the case of the Kupferschiefer deposit in Poland, more than 100 $km^2$. In the sandstone subtype, hydrogen sulfide within a reservoir of natural gas reacts directly with dissolved copper in the ore fluid to precipitate copper sulfides, and methane of the natural gas acts as a reductant to form further sulfide by reaction with ore fluid sulfate. The newly formed sulfide can also react to precipitate copper sulfides. Sandstone deposits tend to be thicker than reduced facies, but are not as extensive in area and are tabular to lens-like in shape (thicknesses around 20 m and areas of 5 $km^2$ are common). Finally, in the red-bed subtype deposits, carbonized plant fossils within gray fluvial sandstones isolated within the clastic sequence of red sedimentary rocks serve as the reductant for ore fluid sulfate. Red-bed deposits are typically only meters thick, are elongate within the ribbon-like host sandstone, and have areas generally less than 1 $km^2$ (Hayes and others, 2015). Red-bed copper deposits are commonly too small to be profitably mined in today's global copper market.

### Geology and Occurrence in the Study Area

There is potential for sandstone-type sediment-hosted stratabound copper deposits in the Fossil Basin and Bear Lake Plateau blocks of the Bear River Watershed study area. There is also potential for red-bed-type deposits, and there is conceptually a chance for reduced facies deposits, though no reduced facies-type occurrences are known. Both red-bed and sandstone types occur to the north or northwest of the proposed withdrawal area.

The Griggs Mine in Lake Alice district, Wyoming, is 37 km (23 mi) north from the northern boundary of the Fossil Basin block and 40 km (25 mi) north of the northern boundary of proposed withdrawal area in that block. It was discovered in 1895, operated 1915–1920, and was examined and reexamined during World War II and later in the 20th century before being reclaimed as a private summer cabin site on patented land (U.S. Geological Survey, 2016). The Griggs Mine is on a thrust sheet that is continuous into the proposed withdrawal area (fig. 26). The Griggs Mine and five other copper occurrences in the Lake Alice district are hosted by the upper part of the Nugget Sandstone of latest Triassic and earliest Jurassic age (fig. 6) (Love and Antweiler, 1973). The Nugget Sandstone is composed mostly of wind deposited dune sands like the correlative Navajo Sandstone of the Glen Canyon Group on the Colorado Plateau, and the Nugget is almost everywhere red, except for the places that host copper mineralization and places where the Nugget produces petroleum (fig. 26). The Nugget is the most important reservoir rock for thrust belt oil and gas in Wyoming, Utah, and Idaho (Powers, 1983). The Griggs Mine is a sandstone-type copper deposit and has cap rocks of dolomitic breccia impregnated with pyrobitumen, a hard black organic substance like solidified tar that occupies former pores and fractures. The cap rock is part of the Gypsum Spring Formation (or Member of the Twin Creek Limestone). The original seal rocks for a gas reservoir may have been evaporitic rocks, perhaps anhydrite, which would have been consumed by reaction with the natural gas. The average grade from five samples of ore from the Griggs Mine analyzed by Love and Antweiler (1973) was 2.66 percent copper, 280 g/t silver, and 1.43 percent zinc, but two of the five were labeled "selected high-grade samples." Osterwald and others (1966, p. 56) state that in 1919, 15 [short] tons of Griggs ore brought $1,180. At a price of 18.18 cents per pound of copper that year (Inflation Monkey, 2012), that calculates to a grade of 21.63 percent copper in the shipment, an astronomical grade for sandstone copper ore that probably records that the shipment was carefully hand-sorted to include nothing but almost pure copper-carbonates. Osterwald and others (1966) later report that in 1942, Griggs ore averaged $18.00 per short ton [in value of its contained copper]. At an average price of 12.27 cents per pound from that year (Inflation Monkey, 2012), the produced grade for the year calculates to 7.33 percent copper, still far too high a grade to be run-of-the-mine ore, still reflecting selective hand sorting of the ore that was shipped. Worldwide, the median grade of mined sandstone-type copper deposits is 1.2 percent and the median silver grade is 19.5 g/t (0.51 troy oz per short ton) (Zientek and others, 2013b, p. 44). The worldwide median tonnage of mined sandstone-type copper deposits is 10 million metric tons (Mt), while the mean tonnage is 77 Mt (Zientek and others, 2013b). The largest sandstone copper deposit in the United States is Rock Creek, Montana, which contains 137 Mt of 0.72 percent copper and 54 g/t silver (Couture and Tanaka, 2005).

Three red-bed-type copper occurrences, the Bonanza Mine, the Bonneville Mine, and the Evening Star claims, lie west of the Fossil Basin block and north of the Bear Lake Plateau block (figs. 26 and 27) (Gale, 1909). These three occurrences are hosted by the Triassic Ankareh Formation red-bed sequence (fig. 6) in gray sandstone beds containing carbonized plant fossils. A fourth red-bed-type copper occurrence, the Cockscomb (figs. 26 and 27), is hosted by the Lower Cretaceous Gannett Group and also in gray sandstones within that red-bed sequence. The Cockscomb occurrence is south of the Fossil Basin block and east of the Bear Lake Plateau block (fig. 27). The Rock Creek Valley copper occurrence, within the proposed Fossil Basin withdrawal area (fig. 27), is hosted by the Pennsylvanian Weber Sandstone (fig. 6) and is probably a sandstone type occurrence.

### Exploration and Mining Activity

Since the time of operation of the Griggs Mine during World War II, there has apparently been little or no mining or exploration for sediment-hosted stratabound copper deposits in the area of the Fossil Basin and Bear Lake Plateau blocks. Based on BLM data (see Dicken and San Juan, 2016b), the only claims for copper near the study area are the patented lode claim group at the Griggs Mine itself. There are no pending and no authorized surface management plans for copper mining within or near the proposed withdrawal areas.

### Potential for Occurrence

The presence of the Griggs Mine and other sediment-hosted copper occurrences demonstrates that a copper mineralizing system was present in the thrust belt. The best host rocks are mapped sufficiently to predict their location within the study area, even beneath cover. The sites of localization of mineralization are predictable—they were formerly petroleum traps. In addition, although the known copper occurrences are not densely distributed, there are red-bed-type copper occurrences several kilometers to the west and south of the Fossil Basin block, and there is a single sandstone-type copper occurrence, Rock Creek Valley (fig. 27), within the Fossil Basin proposed withdrawal area.

A tract consisting of a number of north-trending elongate strips of land has been constructed, consistent with earlier USGS assessments for sediment-hosted stratabound copper deposits (for example, Zientek and others, 2014). Earlier assessments for sediment-hosted stratabound copper deposits identified whole basins as permissive for this type of copper mineralization (Parks and others, 2016). The whole depositional basin of the Nugget Sandstone is inappropriate to consider for this assessment. Earlier assessments for sediment-hosted stratabound copper deposits identified lands that had prospective host rocks at the surface or in the subsurface and then assessed those lands to a depth appropriate for the kind of mining that would be needed and with the expected value of the ore. In this assessment, the potential for deposits of this type is estimated to a depth of 1 km (3,281 ft) below the surface. Permissive tracts were identified as follows.

Geologic maps of excellent quality at 1:62,500-scale are available for the Sage and Kemmerer 15-minute quadrangles (Rubey and others, 1975) and the Cokeville 30-minute quadrangle (Rubey and others, 1980). These geologic maps are accompanied by east-west geologic cross sections constructed at 4.6 km intervals north to south. Eleven of these cross-sections cover the Fossil Basin block.

The cross sections, together with their corresponding geologic maps, were used to identify all areas where the Nugget Sandstone is known to be, or projects to be, present at less than 1 km depth within both the Fossil Basin and the Bear Lake Plateau blocks. The separated strips of the tract are each controlled by some particular relation between the Nugget Sandstone, the major thrust faults, the accompanying folds, and the erosion surface. Each relation continues parallel to a particular thrust fault for several kilometers up to several tens of kilometers.

The area of the Bear Lake block is almost entirely covered by the Logan 30'×60' quadrangle mapped at scale of 100,000 by Dover (1995). This geologic map covers a north-south extent larger than the combination of the Sage and Kemmerer, and Cokeville quadrangles by Rubey and others (1975; 1980). Three cross sections across the Logan quadrangle (Dover, 1995) are spaced approximately 18 km apart. Therefore, the precision of the tract defined using the Logan map (Dover, 1995) is considerably less than that attained using

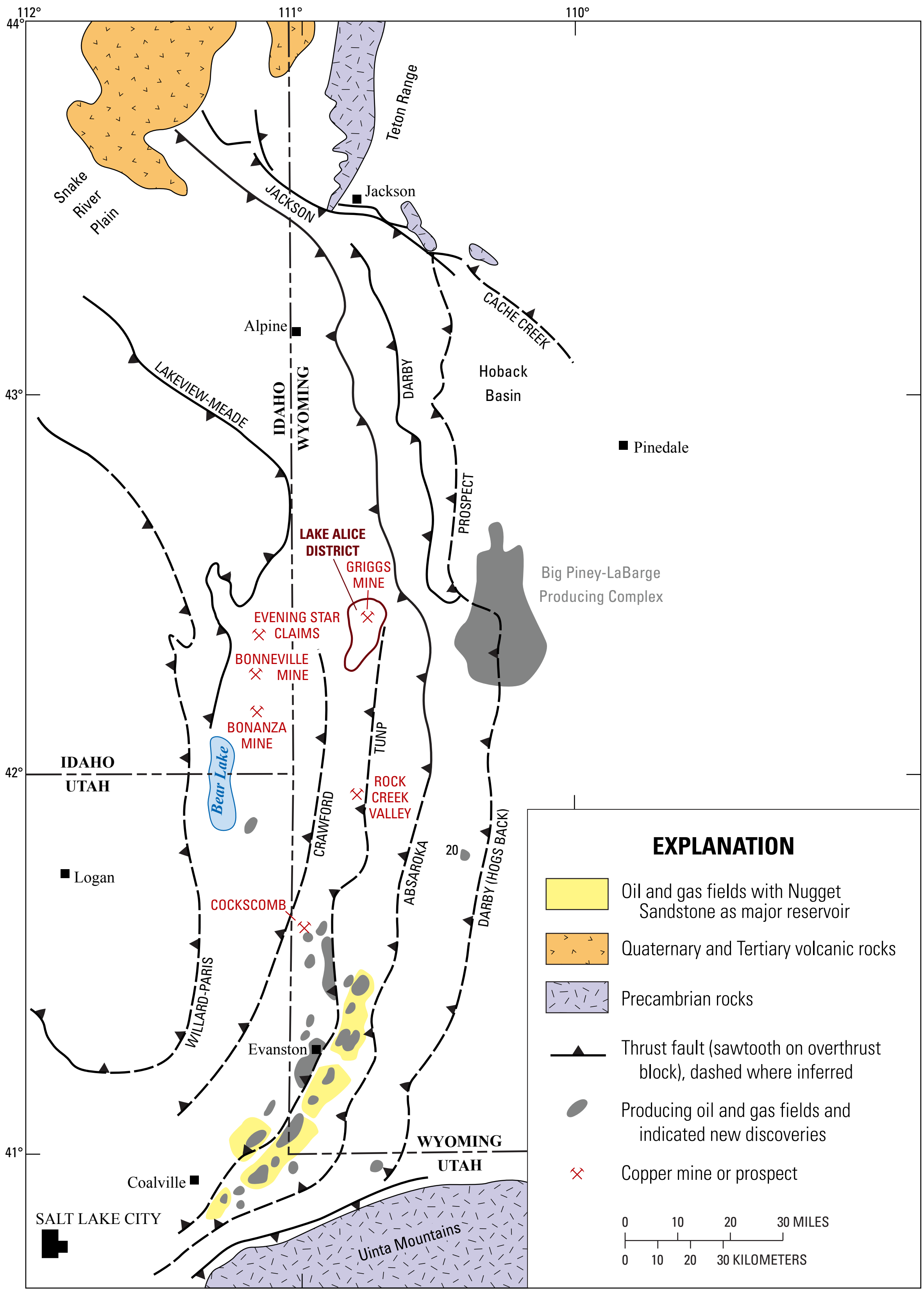



**Figure 26.** Map showing sediment-hosted stratabound copper locations relative to thrust faults and oil and gas fields in the thrust belt. Traces of major thrusts, adjacent basement uplifts, and oil and gas fields are from Powers (1983). Sediment-hosted stratabound copper occurrences are from the Mineral Resources Data System (MRDS; U.S. Geological Survey, 2016) and Love and Antweiler (1973).

11 cross-sections from the Sage, Kemmerer, and Cokeville (Rubey and others, 1975, 1980) quadrangles.

The areas in which the Nugget Sandstone is within a kilometer of the surface in Utah are not geologically different than those in Wyoming. There is no reason to judge those in Wyoming with greater potential based only upon the one or two copper occurrences. As a result, we have included all of the strips of land with the Nugget within 1 km of the surface into a single tract for potential and certainty rating.

There are no known copper occurrences in the Nugget Sandstone in the Logan quadrangle. Results from USGS stream sediment and soil sampling were examined for the entire Bear Lake Plateau and Fossil Basin PLSS blocks, and there are no anomalous areas, nor even anomalous single samples. Also, there are no surveys by geophysical methods appropriate for exploring for this deposit type. However, given that (1) the Alice Lake district, to the north, is on a thrust sheet that extends continuously southward into the Fossil Basin block and contains the Rock Creek Valley copper occurrence, and (2) the copper mineralizing system extended at least from the red-bed-type occurrences in Idaho to as far south as the Cockscomb occurrence (fig. 26), we estimate the mineral resource potential as moderate (M). Evidence for potential is direct in the form of the sandstone-type Rock Creek Valley copper occurrence, yet the single occurrence is quantitatively minimal, which requires a certainty assignment of C.

### Economic Analysis of the Deposit Types

Sediment-hosted stratabound copper deposits are typically higher grade than porphyry copper deposits, the world's largest-producing copper deposit type. Sediment-hosted stratabound copper deposits also commonly have byproduct or coproduct silver (Hayes and others, 2015). There are insufficient numbers of known occurrences in the assessment region to permit a prediction of deposit tonnages. Although sandstone-type copper deposits can have large tonnage (median of 10 Mt and mean of 77 Mt), the only example in the area, the Griggs Mine, was a shallow mine operated along just 305 m (1,000 ft) of length. Production and resource information for the Griggs Mine is not available. Another deposit like Griggs is unlikely to be economically viable in this area in the foreseeable future. However, potential for undiscovered copper resources in deposits of 10 Mt and perhaps more is considered possible.

Most of U.S. the copper production is from large, open-pit porphyry-type deposits, not from sediment-hosted stratabound deposits. It has been only 2 years since the last U.S. mine in a sandstone-type copper deposit closed after mining more than 90 Mt. Mining is currently proposed at two new sites, the Rock Creek deposit and the Montanore deposit, both in Montana. The Lisbon Valley, Utah, sandstone-type copper deposit continues to produce from three separated ore bodies totaling 48 Mt or 0.47 percent copper (Hahn and Thorson, 2005).

Discussion of the economics of copper can be found in Bleiwas (2016). None of the current copper production attributed to Utah is from the study area.

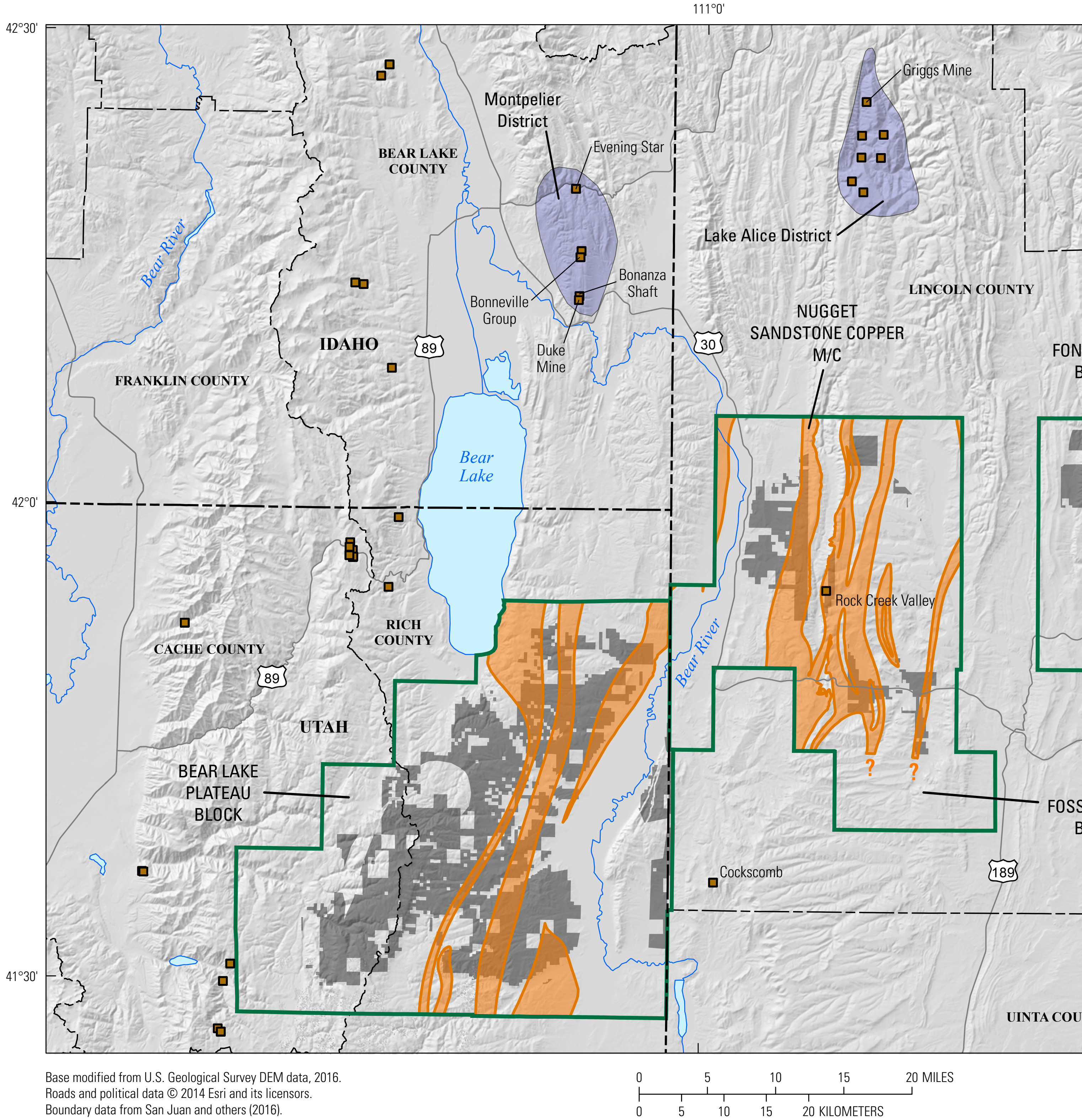
## Banded-Iron Formation

### Mineral Description

Banded-iron formation is sedimentary rock characterized by alternating iron-rich and silica-rich layers. The thickness of individual layers is typically a few millimeters to a few centimeters. Overall, an iron formation may be meters to hundreds of meters thick. The principal iron minerals are hematite, magnetite ($Fe_3O_4$), siderite or another iron-carbonate, or pyrite, or less commonly, an iron silicate such as stilpnomelane ($(K,Ca,Na)(Fe^{2+},Mg,Fe^{3+})_8(Si,Al)_{12}(O,OH)_{27}\cdot nH_2O$). The iron formation is designated as carbonate facies, hematite-facies, or the like, dependent on the most important iron mineral. The iron minerals present today are not those that were chemically precipitated from seawater but are those that formed during diagenesis after burial and during metamorphism of the rocks. Algoma-type iron formations are those in Archean rocks. They are generally found in relatively thin units (meters to tens of meters) within sections dominated by volcanic rocks, pelitic rocks, and chert. See appendix 3 in Day and others (2016) for a more detailed discussion of the banded-iron (Algoma-type) mineral-deposit model.

### Geology and Occurrence in the Study Area

In the Archean rock section that hosts the South Pass-Atlantic City district, the Miner's Delight Formation graywackes are interpreted to be stratigraphically underlain by the Roundtop Mountain Greenstone, which is comprised of mafic metavolcanic rocks, originally pillow basalts at places. Stratigraphically below the Roundtop Mountain Greenstone is the Goldman Meadows Formation, which consists of pelitic schists, intercalated magnetite-facies banded iron formation, and, near the bottom, a single 6- to 12-m thick unit of quartzite. In detail, Bayley (1963) recognized and mapped two intervals of magnetite-facies banded iron formation. The lower is 6 to 18 m thick, and the upper or main iron formation is 43 to 49 m thick. The iron formations are exposed on both flanks and around the nose of a complex, isoclinal syncline, overturned to the east, which has been faulted and deformed by extreme compression. Without the extreme compression during the Archean, there would be no Atlantic City iron ore body because, on the northwestern limb of the syncline, the extreme compression and faulting has thickened the iron formation by repetition on reverse faults from about 46 to 183 m. The Atlantic City iron mine, immediately north of the northern boundary of the South Pass block, operated in the area of thickened iron formation, removing 82 Mt (90 million short tons) of ore between 1962 and 1983 (Hausel, 1991, p. 28–29). The original resource announced by U.S. Steel Corporation was 110 Mt (121 million short tons) of proven reserves at 25 to 32 percent




Base modified from U.S. Geological Survey DEM data, 2016.
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Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

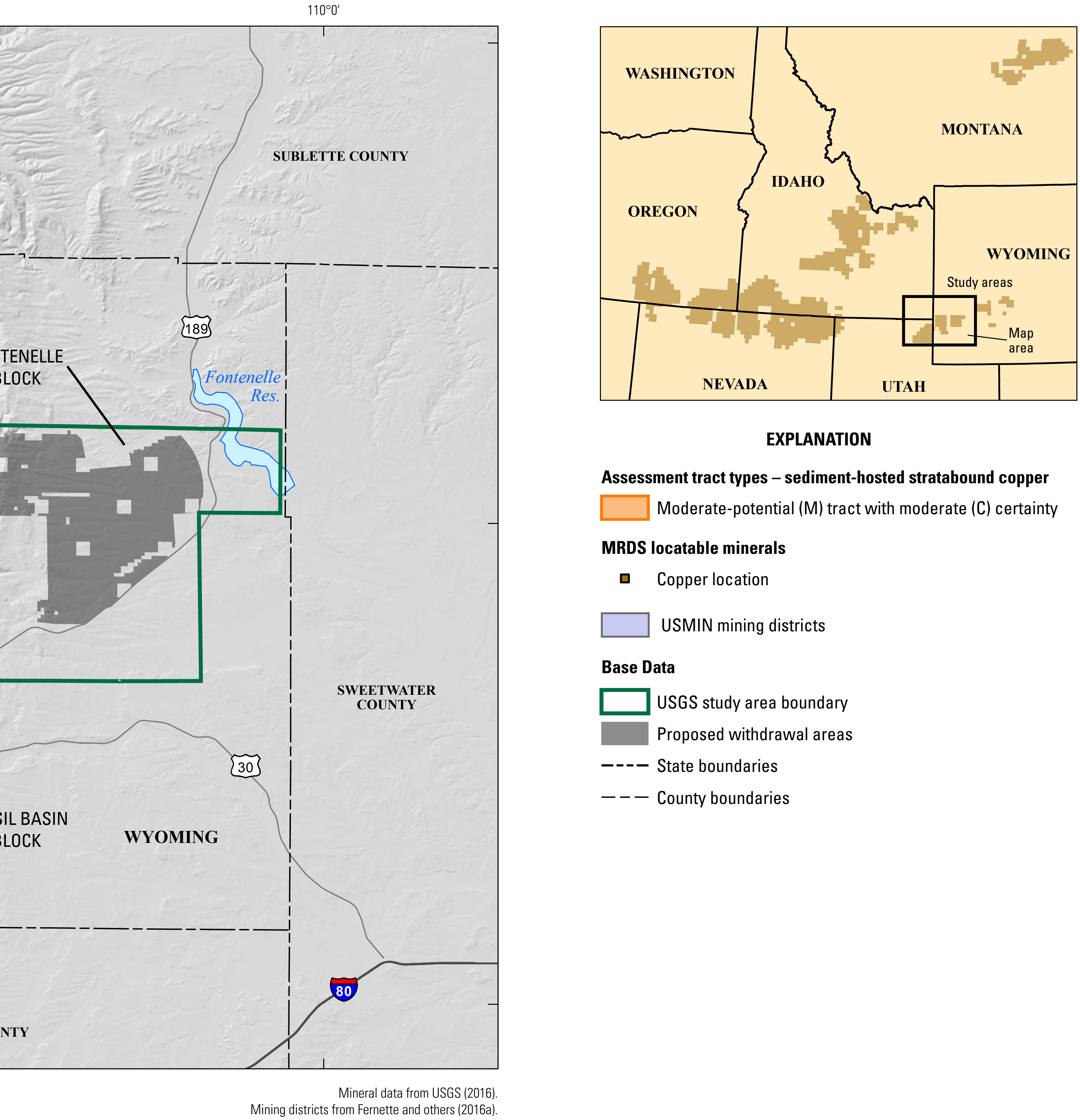



**Figure 27.** Map showing the mineral-potential tracts for sedimentary-hosted copper deposits in the Bear River Watershed study area, Wyoming and Utah. USGS, U.S. Geological Survey. MRDS, USGS Mineral Resources Data System. USMIN, USGS Mineral Deposit Database.

iron, and 273 Mt (300 million short tons) of indicated ore at 22 to 35 percent iron (Anonymous, 1960, p. 27). There are ten smaller concentrations of iron ore northeast and southwest of the Iron Mountain Mine. (Bayley, 1963, p. C22). Resources in those smaller deposits are not known.

Bayley and others (1973, plate 1) show the main iron formation in the Goldman Meadows Formation pinching out entirely, in outcrop, in T. 29 N, R. 100 W., sec. 8 (fig. 17), 6,280 m south-southwest from the center of the ore body of the mine (which he labels "U.S. Steel Corp. iron mine"). Hausel (1991, plate 1) depicts the southwestern end of the Goldman Meadows Formation differently than Bayley and others (1973). He places the southwestern-most outcrops of the main iron formation about 6,920 m south-southwest from the center of the pit lake. There, Hausel (1991) shows the iron formation, about 30 m thick (or a little less), descending beneath Tertiary and Quaternary cover. Although the overlying Roundtop Mountain Greenstone re-emerges to the southwest from below the younger sediments, the Goldman Meadows Formation and underlying Diamond Spring ultramafic rocks do not. In either case, the iron formation disappearance from outcrop, though it is inside the northern-most PLSS township in the block, is at least 3 km northeast of any proposed withdrawal area in the South Pass block. There does not appear to be any signature on airborne magnetic surveys that could be interpreted as magnetite-facies banded iron formation. For that reason, we made no assessment of the potential for banded iron formation-hosted iron deposits.

#### Economic Analysis

The relatively low grade (about 30 percent iron) of the Atlantic City ore would make reopening that mine difficult at this time. Currently, "direct shipping" hematite ore that has in excess of 56 percent iron is produced from large deposits in Australia and Brazil, and, except in China, that hematite ore dominates world production (Tuck, 2016; Geoscience Australia, 2014). At the Atlantic City mill, ore was crushed, ground, and magnetically separated, then pelletized to form taconite pellets, which were roasted, and then shipped by rail to a steel mill in the Salt Lake City area (Bayley, 1963).

Discussion of where iron is being produced in the Western United States can be found in Bleiwas (2016). None of the current production of iron is from the study area.

### Sandstone Roll-Front Uranium

#### Mineral Description

Sandstone roll-front uranium deposits are formed by reduction precipitation of the uranium minerals uraninite ($UO_2$) and, in places, coffinite ($U(SiO_4,(OH)_4)$). Typically, oxygenated uranium-bearing paleo-groundwater moved downdip by gravity within gently dipping permeable fluvial sandstone beds (Fischer, 1974; Boberg, 2010). Reducing conditions are encountered along the groundwater flow path due to the presence of organic carbon buried within the original sediments or by seepage of hydrocarbons into the sediments (Boberg, 2010), and ore minerals precipitate near the transition between oxidized and reduced sedimentary rocks (Fischer, 1974; Boberg, 2010). Uranium in the paleo-groundwater is derived from uranium-enriched surficial water resulting from the leaching of ash-fall tuffs and deeply weathered Precambian rocks (Boberg, 2010; Dahlkamp, 2010). Sandstone roll-front uranium ore bodies are variably crescent-shaped in cross section, with the tails pointing updip, and are irregularly linear in plan view (Dahlkamp, 2010). The richest ore tends to be concentrated along the concave edge of the reduced (unaltered) zone within the crescent (Fischer, 1974; Dahlkamp, 2010). A large sandstone roll-front uranium deposit may be a few tens of meters in stratigraphic thickness and in lateral width, and it may extend hundreds of meters along the oxidation-reduction front (Fischer, 1974).

Across a typical sandstone roll-front uranium ore body, variations in the uranium content are detected by gamma logs, and mineralogical zonations reflect processes of alteration due to oxidation and precipitation by reduction (fig. 28) (Boberg, 2010). Within the ore zone, uraninite and coffinite are finely disseminated as cements in gray, pyritic sandstone. The sandstone ore also contains carbonized plant fragments and patches of calcite cements. The gray, pyritic ore lies immediately adjacent to a change laterally (towards the interior) in the same sandstone beds to ferric-iron minerals like earthy hematite and earthy orange goethite (Dahlkamp, 2010). With the exception of calcite and some of the pyrite, all of the authigenic minerals in the system are very fine-grained. Uraninite and coffinite are commonly "sooty."

The typical reduction/oxidation (redox) "front" is a sharply defined color boundary visible in the sediments that has a crescent shape in cross section, crossing through bedding and lamination, concave towards the ferric-iron mineral (oxidized, altered) side (fig. 28, row D; Rubin, 1970; Fisher, 1974; Boberg, 2010; Dahlkamp, 2010). Uranium ore, as much as 7.5 m thick, but typically less, lies immediately adjacent to the roll front and extends laterally from the redox boundary within gray sandstone for several tens to, at rare places, 600 m into a basinward "seepage zone" (Rubin, 1970) before thinning to the bottom of the sandstone and grading out (fig. 28, rows B and D). Farther into unaltered gray sandstone, the rock has a small background amount of pyrite and calcite. Both pyrite and calcite are most abundant near the redox front on the unoxidized side. Oxidized sandstone with colors of grayish pink or grayish yellow, colored by hematite grain coatings or limonite grain coatings respectively, in the same stratigraphic unit, may extend for miles or even tens of miles, typically toward basin margins. Sandstone within the altered tongue may have goethite pseudomorphs after pyrite for a few hundred feet or less from the front or even a small amount of very fine-grained pyrite. Carbonized plant fragments also disappear with distance from the front into altered sandstone, but uncommon relicts of reduced rocks within the altered tongue have been found at places, even kilometers into the altered sandstone, and some contained high concentrations of uranium. Calcite cements are generally absent from the altered tongue. In map view, the roll-front in a single sand body is irregular, but it is common for lobes of alteration to be kilometers across and convex towards the center of a basin.

Ore grades and thicknesses are not developed along all of the length of a roll-front, but rather, the ore bodies in map view are like "widely spaced elongate beads on a string" (Fischer, 1974, p. 364). Radiometric equilibrium refers to the ratio of measured chemical uranium grade to the calculated equivalent grade from the natural gamma logs (radiometric equivalent grade). If the ore's radioactive decay products were consistent with the age of the ore, the ore would be considered at equilibrium. If the decay products were greater than expected for the age of the ore, the equivalent grade was higher than the chemical grade and the equilibrium would be considered negative. Generally, the equivalent radiometric grade changes from negative to positive at the redox front. Natural-gamma logging tools were calibrated at pits operated by the Atomic Energy Commission in Casper, Wyoming, such that (radiometric) equivalent $U_3O_8$ grades (e $U_3O_8$) could be calculated in the field. Across most sandstone roll-front uranium deposits, the equivalent grade changed from negative in the altered tongue to positive in ore and farther basinward.

For decades before the late 1970s, Wyoming was the second-leading uranium-producing State in the United States (Boberg, 2010), and all the major production came from sandstone roll-front uranium deposits within lower Eocene or upper Paleocene sandstones. Most of the remaining produced uranium came from roll-front deposits in the Lower Cretaceous Inyan Kara Group on the western flanks of the Black Hills. Only a very small fraction of the production came from deposits of any other deposit type, even though traces of uranium mineralization are found scattered through virtually the entire stratigraphic section in Wyoming, from Precambrian to Quaternary rocks (Boberg, 2010).

In central Wyoming, sandstone roll-front uranium deposits occur in sandstones in four different basins separated by Laramide uplifted, Precambrian-cored mountain ranges. Sedimentation patterns demonstrate that the ranges contributed enormous volumes of feldspathic to arkosic sand to the Wind River, Powder River, Shirley, and Great Divide Basins (listed in clockwise order starting in the northwest).

After the earliest post-World War II flurry of discoveries of outcropping uranium ore bodies using Geiger counters and scintillometers on the ground, most exploration for sandstone roll-front uranium deposits in Wyoming employed "interpolative" drilling without prior geochemical or geophysical surveys. Companies explored claim blocks that had quickly blanketed all of the edges and into the middle of basins using relatively inexpensive rotary drilling with light muds. A geologist logged the drill cuttings, and a contract well logger logged the holes using a combination of resistivity, self-potential, and natural-gamma downhole logs. The geologist in the field was responsible for recognizing lithologies, interpreting altered versus unaltered rocks in tens of different sandstone intervals penetrated by the drill, and then placing the next hole. Where a first hole penetrated altered sandstone, and a second penetrated unaltered rock in a same sandstone unit, a third hole would be placed midway between the first two; then a fourth midway in the shortest gap between altered and unaltered; and so forth until a next hole cut the actual roll-front mineralization. Recognition of the tongue of altered sandstone was critical, and gamma log signatures of "remote barren" (also called "tails"), of "limb ore," of "near seepage," and of "remote seepage" zones were used together with cuttings logs in the interpolation process. Applying a broadly similar exploration method would be the best approach to evaluate the potential for sandstone roll-front uranium deposits in the Big Sandy and Continental Divide blocks. Drill hole data are crucial to evaluating those proposed withdrawal areas.

### Geology and Occurrence in the Study Area

Neither the Big Sandy nor the Continental Divide blocks contains any known uranium occurrences. However, both these blocks are down-dip and basin-ward from places where there are occurrences and documented radiometric anomalies. Specifically, there are known occurrences and radiometric anomalies in the Wasatch Formation (fig. 29). Wasatch sandstones that underlie younger formations to the south or southwest might, therefore, also host sandstone roll-front uranium deposits beneath the Big Sandy or Continental Divide blocks. Areas that are the roots of alteration tongues typically contain widely scattered uranium mineralization that is focused in mudstones, rather than sandstones, or mineralization that is found in relict carbonized plant fragments. In a few places, relict mineralization of roll-front tails or limbs contained enough uranium to support a short-lived, small-scale mining operation. Occurrences found in the Wasatch Formation west of Oregon Buttes and south of the Continental Fault were short-lived operations, but further details are not available. There is more detail available about the rocks that host radiometric anomalies described by Winterhalder (1954). Anomalies that Winterhalder found on the northwest flank of Oregon Buttes (fig. 29, area labeled 1) were in both the top of the Tipton Tongue of the Green River Formation mudstones and in sandstones at the base of the Cathedral Bluffs Tongue of the Wasatch Formation sandstones. Radioactivity was as much as 20 times background (Winterhalder, 1954). Two additional anomalies to the northwest were both in coarse-grained, arkosic, conglomeratic sandstones. In the anomaly just southeast of Wyoming State Highway 28 (fig. 29, area labeled 2), radioactivity was 13 times background, and in the one farther northwest (fig. 29, area labeled 3), radioactivity was 10 times background. The small past-producing mines and radiometric anomalies are good evidence for the presence of uranium and its mobility in a recharge zone that could be the root for alteration tongues of roll-fronts in the Wasatch that might underlie the Big Sandy and (or) the Continental Divide blocks.

National Uranium Resources Evaluation (NURE) airborne gamma-ray spectrometry coverage was examined above

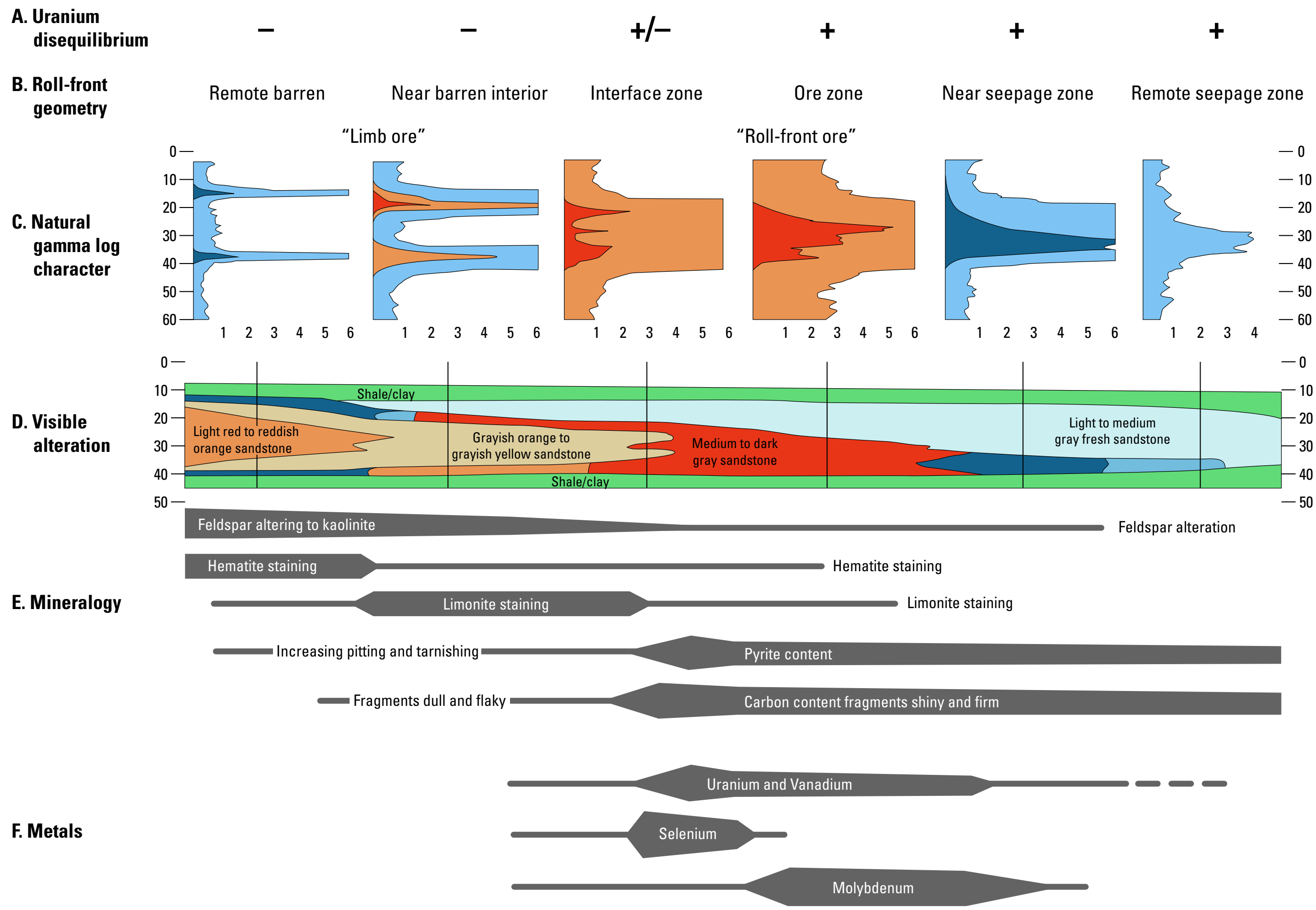



**Figure 28.** Schematic cross section of a sandstone roll-front uranium deposit (redrawn from Boberg, 2010, with permission). Row A, "Uranium disequilibrium," indicates whether chemical uranium will generally be less (–) or more (+) than that calculated from a gamma log of a drill hole. Row B, "Roll-front geometry," introduces commonly used zonation terms. Row C, "Natural gamma log character," shows schematic graphs of downhole gamma logs. (Where the natural gamma log is squared off to the right, it indicates that the first run through the zone went off the scale. A second, or third, run is shown inside that, showing the counts per second at a scale 10 times or 100 times the original scale.) Row D, "Visible alteration," highlights the characteristics, commonly demonstrated by color, of host rocks. Row E, "Mineralogy," plots the presence or absence of common minerals that are subject to alteration and (or) oxidation and precipitation by reduction. Row F, "Metals," plots metal ores commonly associated sandstone roll-front uranium deposit.

the hypothetical recharge zone. No notable anomalies were present for any of the elemental parameters or the elemental ratios (Geometrics, 1978; Geodata International, Inc., 1980; Hill and others, 2009). The airborne gamma-ray spectrometry was flown at 3-mile (4.8 km) line spacing, so small targets could easily have been missed.

USGS stream-sediment and soil sampling geochemical results were examined particularly for uranium (Goodknight and others, 1982; Shannon and others, 1979; Morgan and others, 1981). The USGS National Geochemical Database includes all NURE samples (Smith and others, 2016). The northern part of the hypothetical recharge area (T. 28 N., R. 103 W.; fig 17) was identified as the fifth-best anomaly in the Lander 1-degree by 2-degree quadrangle (Goodknight and others, 1982, p. A-42). Goodnight and others' identification of this area was on the basis of a stream sediment sample that contained more than 6.6 ppm uranium and a second stream sediment sample that had residual uranium greater than 1.15 ppm. Mineralized rock bodies in such a recharge zone are typically small and widely scattered; other sedimentary uranium occurrences were known nearby, but not in the drainage that yielded the anomalous NURE samples.

Probably far more important would be an examination for ferric iron oxide alteration in Wasatch Formation sandstone(s) in the hypothesized recharge zone. Figure 30 shows an outstanding example of what such ferric alteration looks like on images from remote sensing data. The area, known as Red Rim, is the outcropping recharge zone for sandstone roll-front uranium deposits within the Fort Union Formation that underlie the west-central part of the map area. The namesake rim of altered sandstone (labeled "Red Rim" on fig. 30) intersects Interstate Highway 80 about 12 km west of central Rawlins, Wyoming (fig. 3). The surface areas displayed in bright pink are characterized by strong spectral absorption features related to ferric-iron minerals in Landsat 7 imagery (Rockwell and others, 2015; Rockwell, 2013) and indicate the presence of abundant hematite in altered sandstone. The 10- to 15-degree dip of the Fort Union beds is steep enough that erosion-resistant sandstone beds each form discrete hogbacks separated from the next sandstone both up- and down-section. The strong ferric-iron signal is stratabound—that is, confined to certain beds. Identification of the strike and dip of bedding, together with the strong ferric-iron alteration signal, lead to the ability to recognize additional altered sandstone beds to the west-northwest even though those beds to the west do not form prominent ridges. The sandstones to the west are at a lesser dip, 5 degrees or less, and the area of major ferric-iron signal for those is wider than for Red Rim. The major ferric-iron signal for those sandstones is, nonetheless, still stratabound.

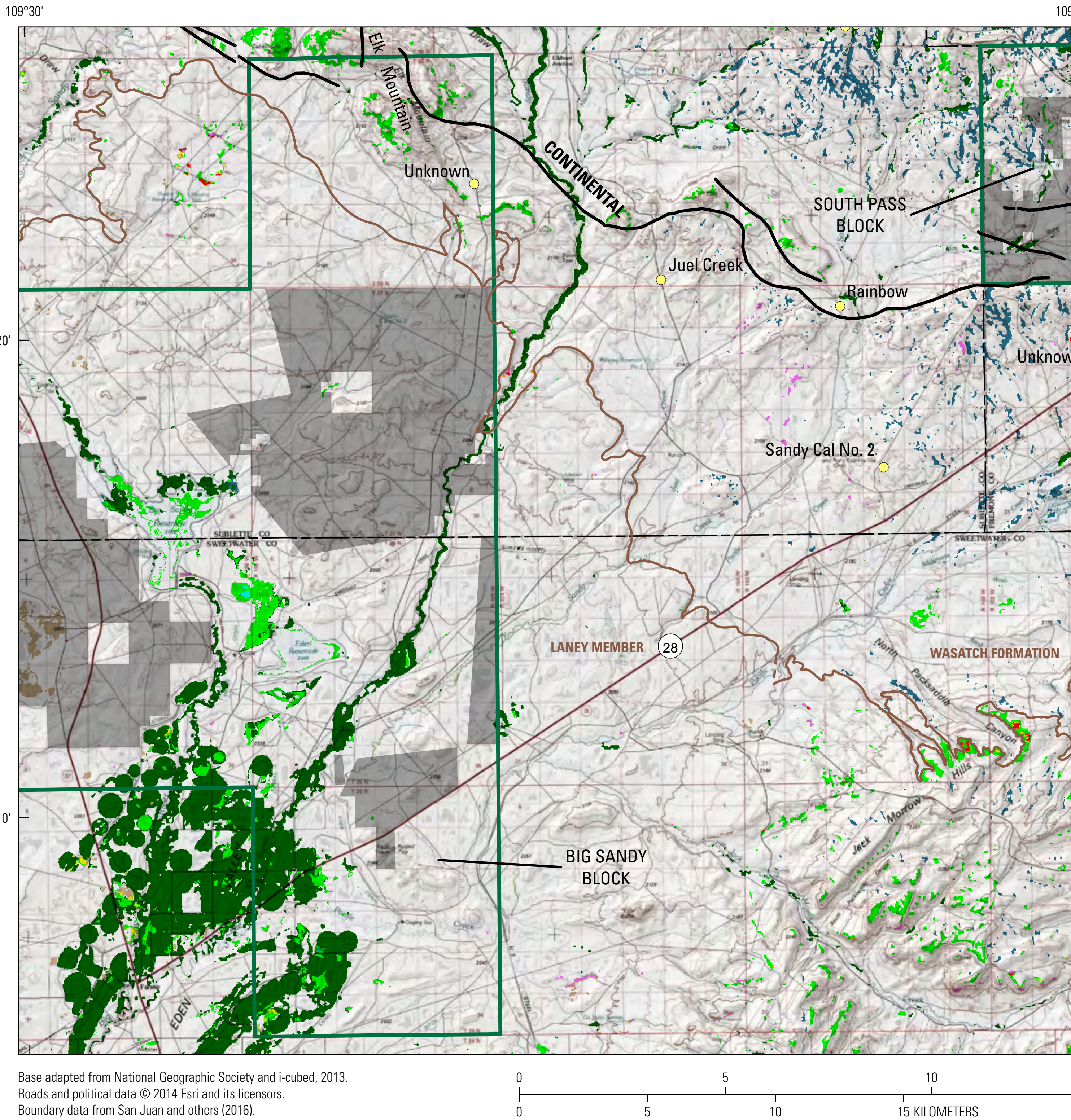
Another example of remote sensing of sandstone roll-front alteration is illustrated in the central Great Divide Basin, which is about 75 km east of the Continental Divide block (fig. 2). The remote sensing signature of ferric iron mineralization in the area around the Sweetwater Mine, a roll-front uranium mine that was open from 1980 to 1983, is shown in figure 31. The Sweetwater district was described by Sherborne and others (1980).

The Sweetwater open-pit mine is about 1 km wide and is incompletely ringed with anomalous iron signatures. It lies between three MRDS locations, the southeasternmost of which is labeled "Sweetwater Mill." There is a combination of altered and unaltered sandstone on the dumps, as well as some additional mineral signals from fresh pyrite weathering to sulfate minerals (green pixels denote "clay, sulfate, mica, marble, and (or) dry vegetation"). Unaltered sandstone there is from the sandstone interval at the ENQ Solution prospect, the next sandstone interval above the sandstone beds in the Battle Spring arkose host rocks at the Sweetwater Mine. (Unaltered ENQ sandstone is from the overburden lying above ore in the Sweetwater sandstone beds.) In figure 31, the network of roads shows in pink, the strong ferric-iron minerals signal, though there are places where the roads don't have that signal. This is not a false signal, however, because these roads were built using the local material, spreading it from its source with a road-grader. The grader spread friable altered sandstone in the directions that the grader traveled. Other studies have found that certain grasses—cheatgrass for example—are characterized by absorptions in the ultraviolet and blue wavelengths similar to those of ferric-iron minerals at Landsat 7 spectral resolution because of their yellow-brown color when they are dry (Rockwell, 2013). These grasses and other dry and (or) dead plant material, may also mimic the spectral characteristics of clay, sulfate, mica, and some pure carbonate rocks at Landsat 7 spectral resolution (Elvidge and Lyon, 1985). However, this area has grasses only within the draws and near the playa lakes. The tops of the low ridges have only sagebrush and some low mound-like plants, similar to some plants in alpine tundra. The ground is about 50 percent bare along the low ridgelines. Slightly above the center of the image in figure 31 the ferric-iron signal is present in several draws, but there still remain some large areas of strong ferric-iron minerals signal that are arrayed in bands running east-northeast. These are the signatures in Landsat 7 images of sandstone roll-front alteration; however these are in broad, rounded outcrops of nearly unconsolidated sandstones, and the beds dip shallowly so that the outcrops are bands up to several hundred meters wide. The beds dip northwest at about 1.7 degrees (calculated from drilling data from 1976). The ENQ sandstone body that forms the overburden at the Sweetwater pit lies at a vertical depth of about 189 m below surface at the northwestern edge of the map area in figure 31. Four discrete sandstone layers each about 15 m thick are exposed and form low rises crossed by the Jeffrey City-Wamsutter road. These four sandstone beds are the next four sandstones up-section from the ENQ sandstone beds, ascending stratigraphically to the northwest.

Figure 31 indicates that the roll-front alteration is stratabound, but at gentle dips, and also shows that grading dirt roads can spread the alteration along their paths. Caution must be exercised when interpreting alteration in this region because of the spectral similarities between dry vegetation and ferric iron, phyllosilicate, sulfate, and carbonate minerals at Landsat 7 spectral resolution.

The same type of processed Landsat 7 imagery as in figures 30 and 31 is shown figure 29, for the Big Sandy and Continental Divide blocks. In the area of exposed Wasatch Formation northeast from outcrop of the Laney Member of the Green River Formation and southwest of the Continental Fault, there are disconnected patches aligned west-northwestward showing the signal of major ferric-iron minerals (shown in pink on fig. 29). In the area between Oregon Buttes (area of healthy vegetation, in dark green, at center right) and Wyoming Highway 28, the Wasatch Formation is involved in the Reds Cabin monocline (Zeller and Stephens, 1969, plate 1) striking northwest and dipping 20 to 50 degrees to the southwest. North of the monocline, the rocks dip gently toward the north; south of it, they dip gently to the south. There are a few patches of likely alteration—two of those are near to and partly overlap the radioactive anomalies from Winterhalder (1954). Thus, the patches of major ferric-iron minerals (pink on fig. 29, areas labeled 2 and 3) signal are stratabound, or nearly so. Winterhalder noted iron staining in the patch to the northwest (fig. 29, area labeled 3). Taken together, the disconnected patches of major ferric-iron mineral signal, the ground radioactive anomalies, and the small past-producing mine (adjacent to 3, fig. 29) constitute permissive evidence for sandstone roll-front uranium-system alteration in that area and also indicate that the altered rocks dip into the subsurface to the southwest and south.

Farther west in the area near the Juel Creek, a past-producing uranium mine, the strike of beds runs broadly parallel to the Continental Fault. To the southeast of the abandoned mine, pink patches (fig. 29) possibly recording major ferric-iron minerals do not run parallel to the fault, and instead, run




Base adapted from National Geographic Society and i-cubed, 2013.
Roads and political data © 2014 Esri and its licensors.
Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

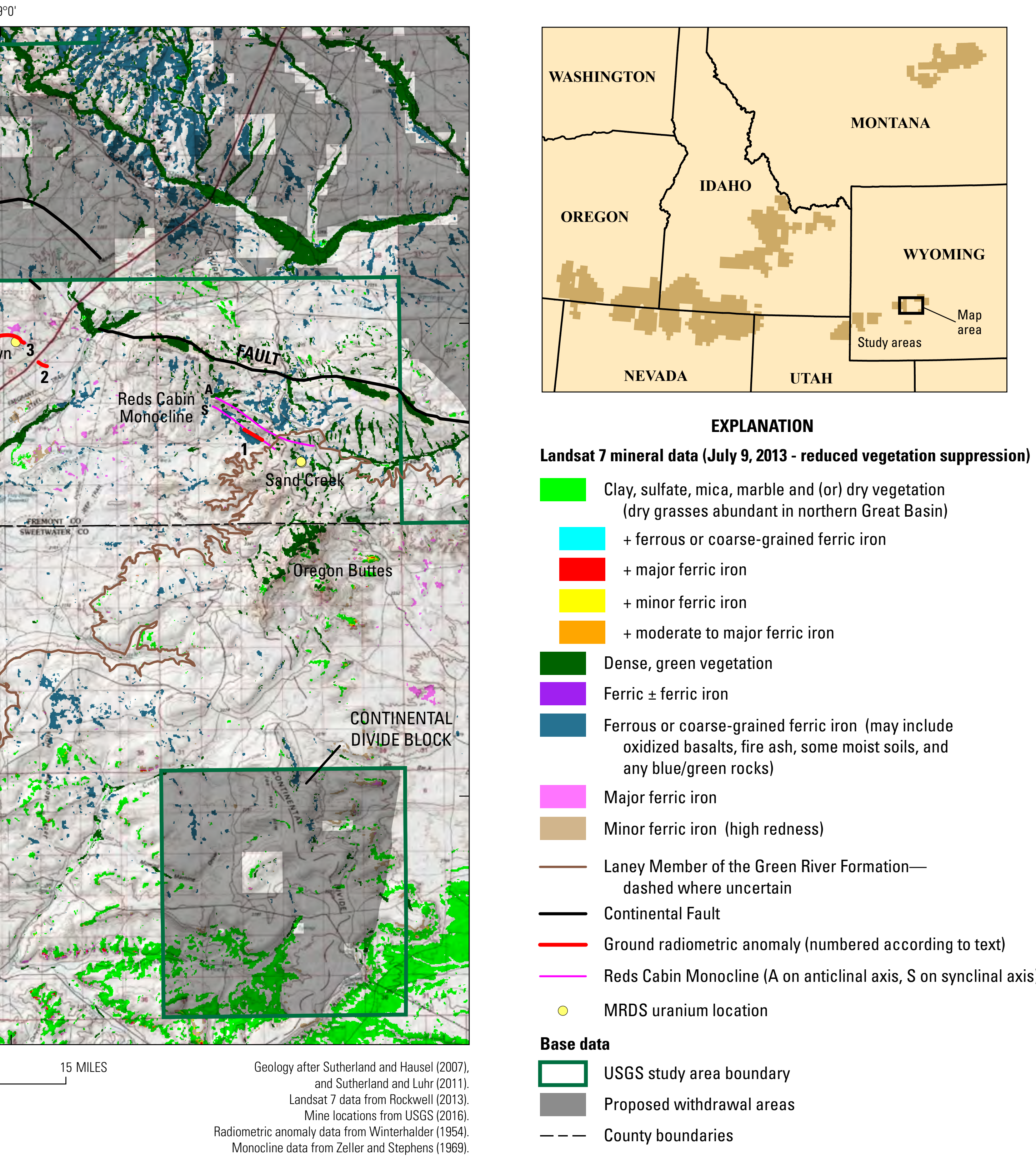
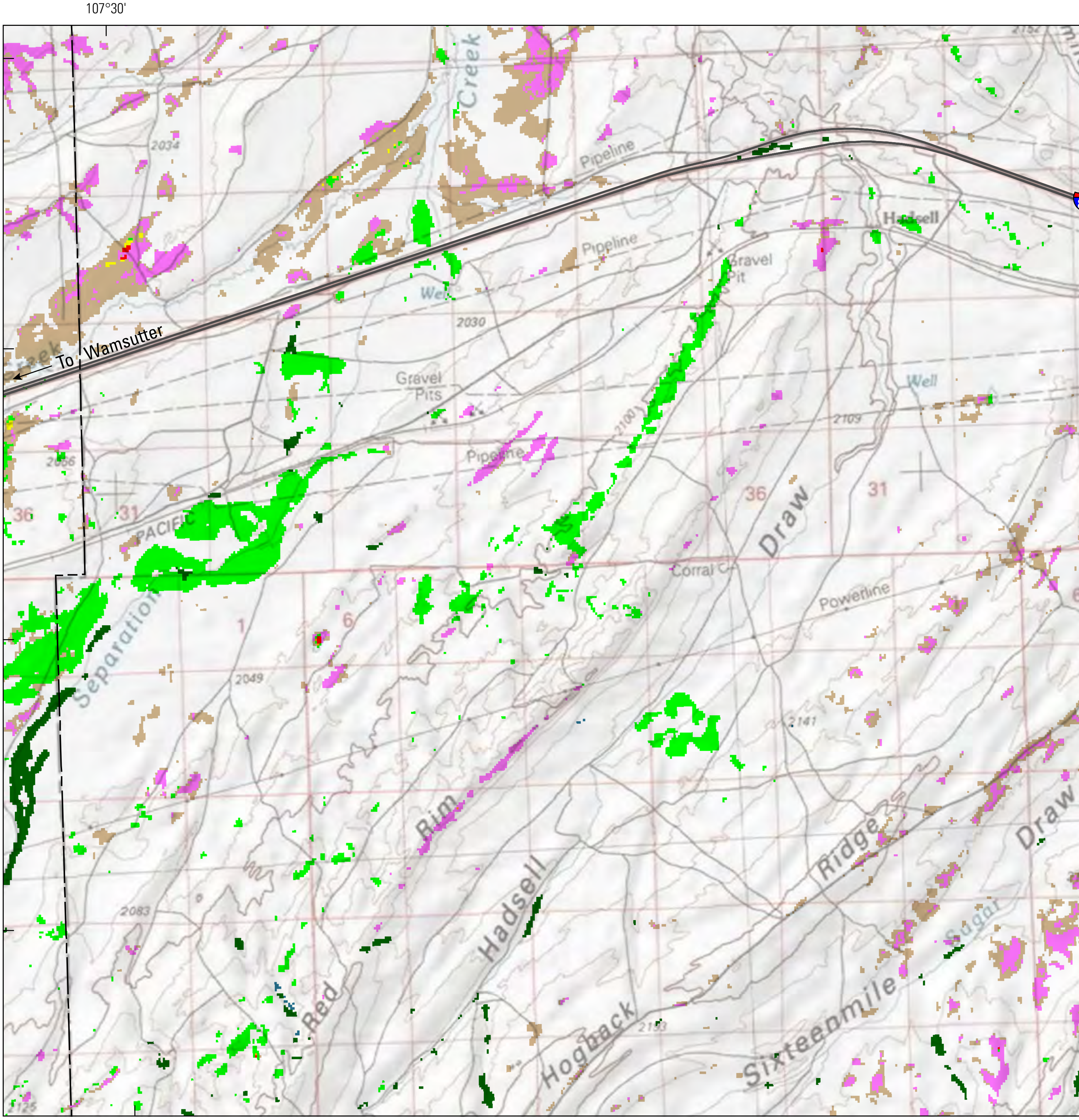
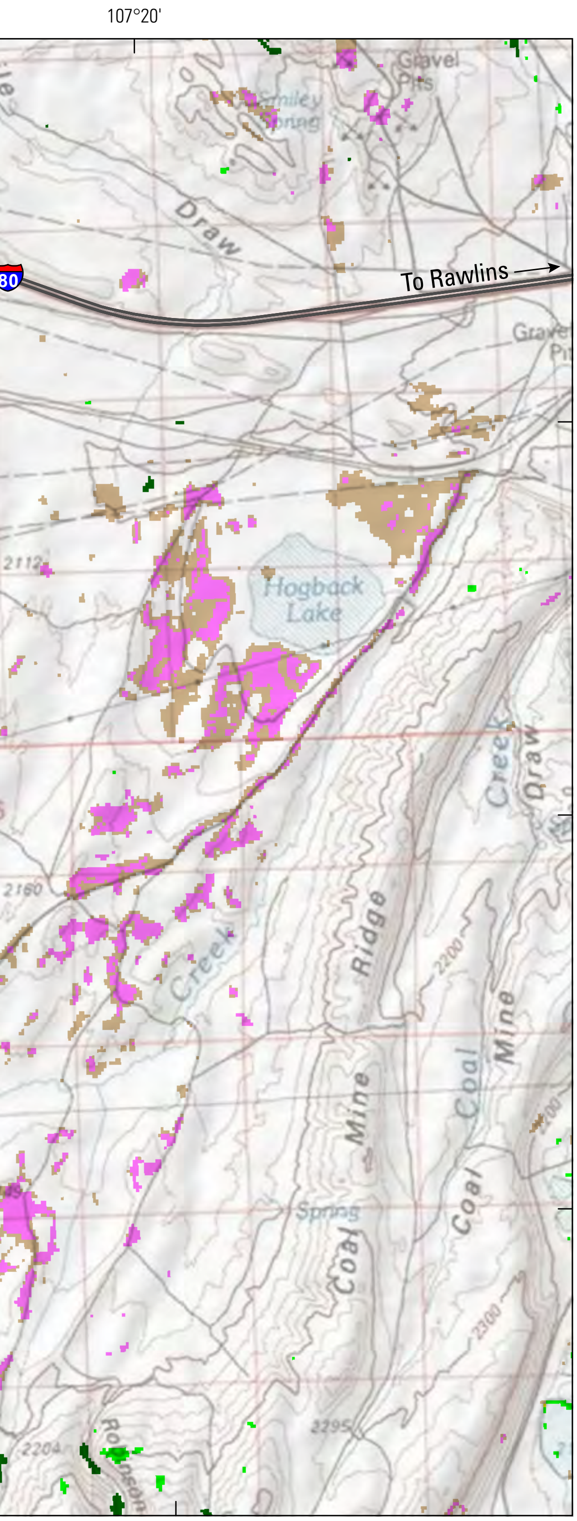



**Figure 29.** Map addressing potential for sandstone roll-front uranium deposits in the Big Sandy and Continental Divide blocks of the Southwestern and South-Central Wyoming study area. The map shows geology from Zeller and Stephens (1969), Landsat 7 spectral mineral signature from remote sensing from Rockwell (2013) and Rockwell and others (2015), past-producing small uranium mines from the Mineral Resources Data System (MRDS; U.S. Geological Survey, 2016), and ground radiometric anomalies from Winterhalder (1954) of the area in the recharge zone to the Wasatch Formation. USGS, U.S. Geological Survey.

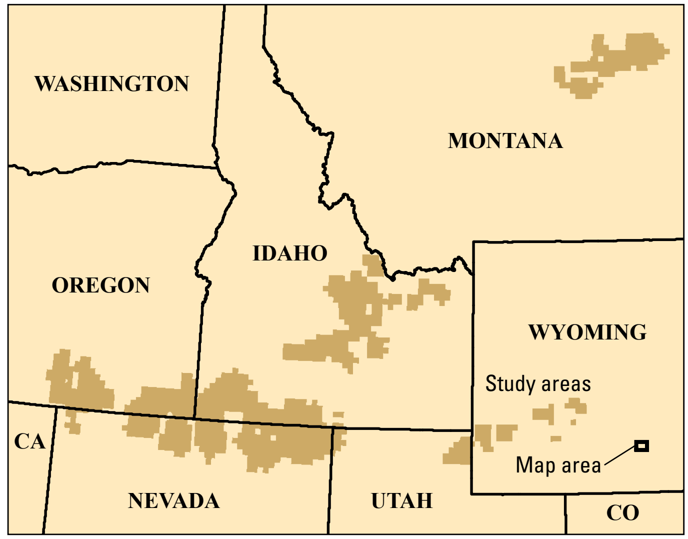



Base modified from National Geographic Society and i-cubed, 2016.
Political data © 2014 Esri and its licensors.
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

0 1 2 3 MILES
0 1 2 3 KILOMETERS




Landsat data from Rockwell (2013).

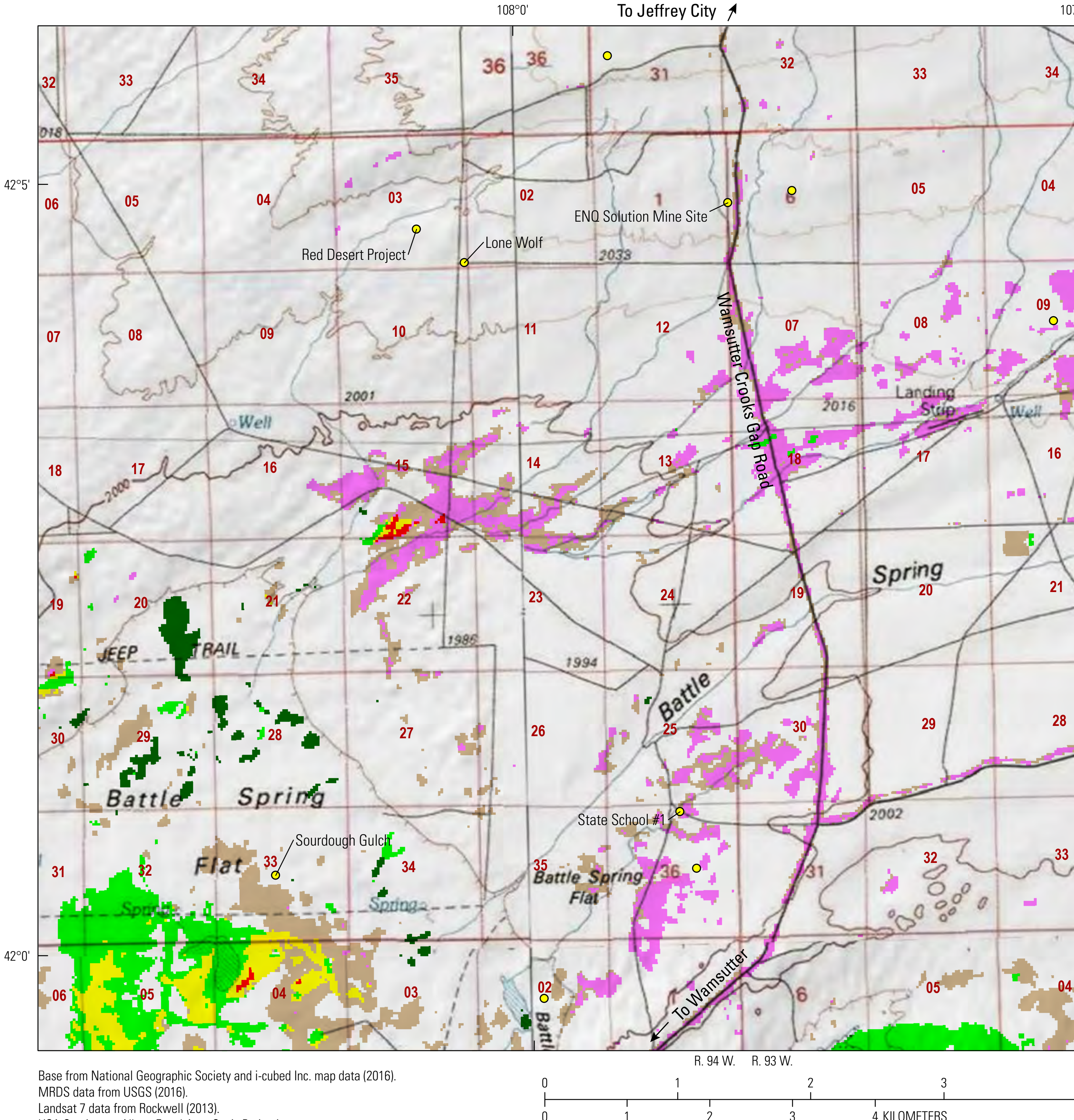



**EXPLANATION**

**Landsat 7 mineral data (July 9, 2013 - reduced vegetation suppression)**

- Clay, sulfate, mica, marble and (or) dry vegetation (dry grasses abundant in northern Great Basin)
- Clay, sulfate, mica, marble and (or) dry vegetation + major ferric iron
- Clay, sulfate, mica, marble and (or) dry vegetation + minor ferric iron
- Dense, green vegetation
- Major ferric iron
- Minor ferric iron (high redness)
- County boundaries

**Figure 30.** Map showing Landsat 7 spectral mineral signature of sandstone roll-front uranium system alteration at the Red Rim area, 11 to 16 kilometers west of Rawlins, Wyoming. Red Rim is about 125 kilometers east-southeast from the Continental Divide block of the Southwestern and South-Central Wyoming study area. Paleocene Fort Union Formation sandstones are altered by sandstone roll-front uranium system processes, producing hematite in the altered tongues in several different sandstones, some of which are also resistant to erosion so that they each stand in elevated outcrops that dip 10 to 15 degrees to the west-northwest. Note major ferric-iron mineral signatures in the sandstones. Sandstone roll-front uranium deposits in the same sandstones down-dip in the subsurface to the west occur within 5 to 11 kilometers. Strong ferric-iron mineral signals to the east are from Jurassic and Triassic red beds.




Base from National Geographic Society and i-cubed Inc. map data (2016).
MRDS data from USGS (2016).
Landsat 7 data from Rockwell (2013).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.

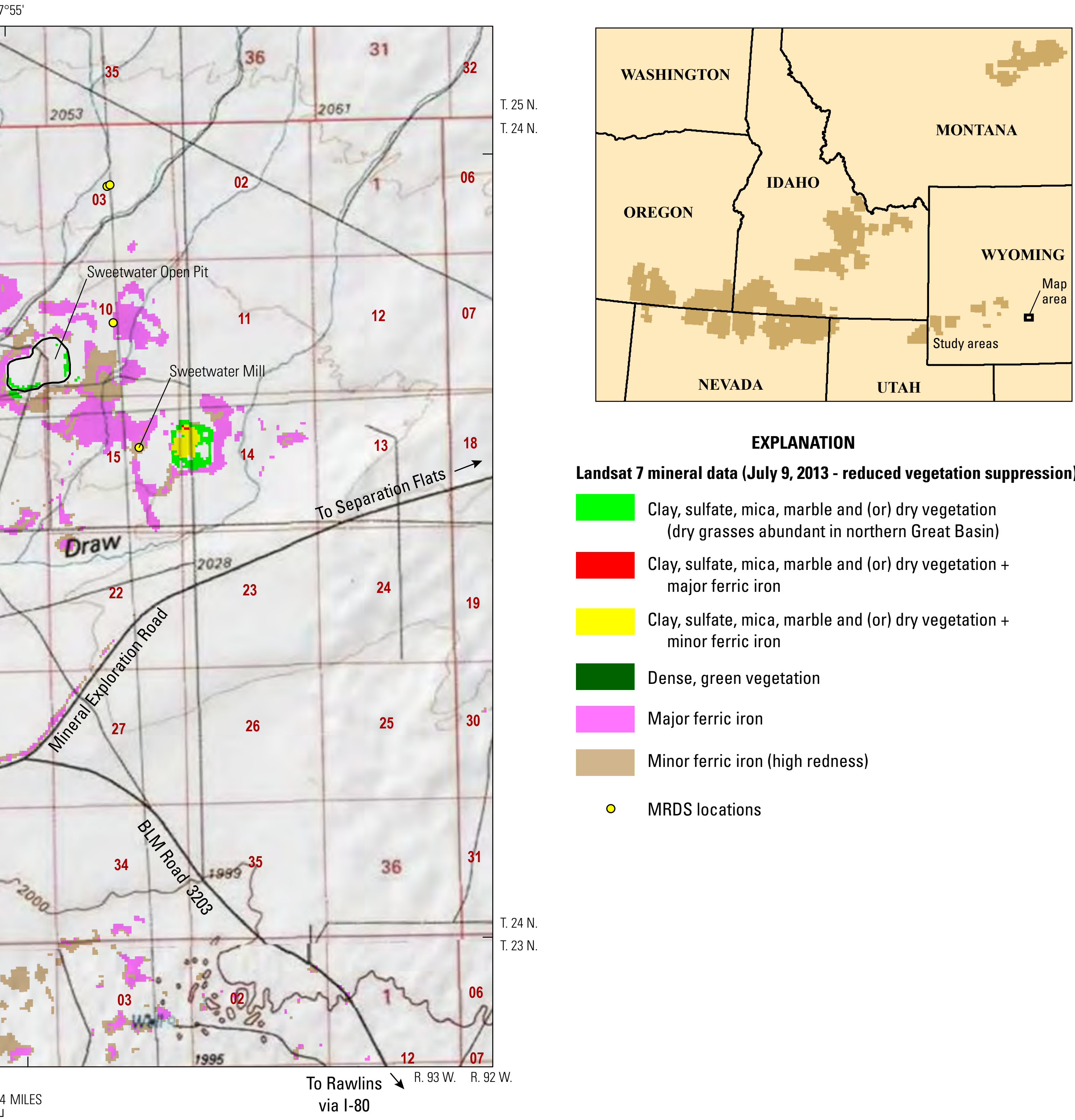



**Figure 31.** Map showing Landsat-7 spectral mineral signatures of sandstone roll-front uranium system alteration in the Sweetwater district, central Great Divide Basin, Wyoming, 72 kilometers east of the Continental Divide block of the Southwestern and South-Central Wyoming study area. MRDS, U.S. Geological Survey (USGS) Mineral Resources Data System.

nearly perpendicular to it, approximately parallel to drainage. The patches are, therefore, interpreted as dry vegetation. Compared with Red Rim, there is little suggestion of possible sandstone roll-front alteration in the Wasatch Formation in this area to the west.

Though the spectral data from satellite imagery can aid the mineral exploration of large areas, data from drill holes is better for the direct assessment of the possibility of sandstone roll-front uranium deposits in the subsurface of the Big Sandy and Continental Divide blocks. Examination of the electronic files of the Wyoming Oil and Gas Commission revealed a few tens of petroleum tests in the area, both within the boundaries of the Big Sandy block and to its north and northeast. About 20 of those were examined by Jim Rogers of the Wyoming State Geological Survey, and about 10 were examined by one of us (Hayes). No logs were recorded for the shallow parts of any of these petroleum tests. Electric logs were available typically starting at 1,830 or 2,440 m (6,000 or 8,000 feet) below surface, far below where the holes penetrated the Wasatch Formation.

H.W. Roehler of the USGS conducted work over several years in the northern Green River Basin and provided measured sections in areas to the south of the Big Sandy and Continental Divide blocks and both within and at the south edge of the Fontenelle block (Roehler, 1990, 1991). His revised nomenclature for the intertongued part of the Green River and Wasatch Formation made the nomenclature of the Fontenelle area conform with the remainder of the basin, which made correlation with the work of Zeller and Stephens (1969, plate 2) possible. As a result, Roehler effectively eliminated all of the main body of the Wasatch Formation in all three of the blocks—Big Sandy, Continental Divide, and Fontenelle—from consideration for sandstone roll-front uranium deposits. In addition, he named two new units of the intertongued Wasatch and Green River Formations in these areas, and these two, the Farson Sandstone Member of the Green River Formation and the Alkali Creek Member of the Wasatch Formation, are units that are considered prospective sandstone intervals for uranium.

On a fence diagram of measured sections and drill hole logs that extends east-west from the proposed withdrawal area in the Fontenelle block to a location just west of the Boars Tusk block, Roehler (1990) correlated rocks of the intertongued Wasatch and Green River interval. He showed that the main body of the Wasatch Formation consists of fluvial, thin-bedded, red mudstone with only minor sandstone intervals. This is a facies of the Wasatch earlier identified by Childers (1974) in the Great Divide part of the basin to the northwest of the Sweetwater district and lying between two paleochannel trends, between Oregon Buttes and the Cyclone Rim area near Bison Basin. This facies, where it consists of red beds representing mudflats (Childers, 1974), cannot be mineralized by a redox roll-front because it is already oxidized, and thus is not reactive with oxidizing uraniferous groundwater. Zeller and Stephens (1969, p. 12) observed that, south of the hypothesized recharge zone, the main body of the Wasatch is characterized by pastel red and purple claystone and mudstone and thick lenticular dusky-yellow coarse-grained sandstone. Thus, the main body of the Wasatch is anticipated to contain no suitable host rocks for uranium mineralization anywhere in the area of the Big Sandy, Continental Divide, and Fontenelle blocks.

Roehler (1990) correlated units throughout the northwestern part of the greater Green River Basin on the basis of his identification of the Shegg's bed of the Tipton Shale Member of the Green River. This correlation placed the Farson Sandstone Member of the Green River Formation (fig. 16) (Roehler, 1991, p. B19–B26) above the Shegg's bed and below any of the oil shales of the Wilkins Peak or Laney Members of the Green River Formation. In its type section on the flanks of White Mountain in section 13, T. 23 N., R. 105 W. (fig 17), at the west edge of the Boars Tusk block, Roehler (1991, p. B25–B26) describes only drab-colored sandstones: gray, tan, or brown, some with calcareous cement. It is doubtful that any of these sandstones, so described, have been altered by roll-front processes. Altered sandstones are pervasively colored pink, orange, or locally, pinkish or orangish gray; they are not mottled with iron oxide concentrations, and the iron oxides do not mineralize strongly along joints or bedding planes. They contain goethitic pseudomorphs of pyrite only where they are within tens of meters to about 300 m of a roll front; otherwise all vestiges of former pyrite are absent. They do not have calcareous cements, nor do they contain carbonized plant fragments. Similar to the White Mountain section, Roehler (1991) describes only drab-colored sandstones in the Farson Sandstone Member in the Alkali Creek section just south of the Fontenelle proposed withdrawal area. Thus, though the Farson Sandstone Member appears to be a suitable host for sandstone roll-front uranium deposits, the best available information suggests that there is no alteration tongue anywhere cutting the fence of holes and measured sections extending from the Fontenelle to the Boars Tusk block. However, similar information is not available for the Farson Sandstone Member to the north, in the hypothesized recharge area for roll-front altered tongues, and the Farson is notably present. Roehler (1991) shows a picture of its bold outcrops in the south-central part of section 21, T. 27 N., R. 101 W. (fig. 17) on the west flanks of Oregon Buttes, where the Farson is north of the axis of the Reds Cabin monocline (fig. 29) and dipping gently to the north. From plate 2 of Zeller and Stephens (1969), the Farson is correlatable with sandstones totaling 68 m thick including 21 m of arkose at its top, lying above the main body of the Wasatch Formation and the recognizable, limestone-bearing Schegg's bed. It underlies the Cathedral Bluffs Tongue of the Wasatch Formation in that area (and is shown that way on plate 2 of Zeller and Stephens, 1969). In 55 m of Cathedral Bluffs section shown on their plate 2, Zeller and Stephens indicate three sandstone units, in ascending order: 8.0 m thick, 6.7 m thick, and 3.0 m thick. In their text they indicate that shades of red characterize the lower half of the Cathedral Bluffs Tongue but that shades of green characterize the upper half. No more detailed information is given. It is nonetheless clear that radioactive rocks, a small past-producing mine, and possible roll-front altered sandstones between Oregon Buttes and Elk Mountain (north of the Continental Divide block, and to the northeast of the Big Sandy block, respectively, fig. 29) are near, in section, to the top of the Farson Sandstone Member and to the immediately overlying lower part of the Cathedral Bluffs. That follows from Winterhalder's (1954, p. 7) identification of the Hiawatha Member of the Wasatch Formation in the same place that Roehler (1991) photographed the Farson Sandstone Member. From there, structure contours on the bottom of the Laney Tongue of the Green River Formation from Zeller and Stephens (1969, plate 1) and attitudes of bedding show that all of the different radiometric anomalies, uranium occurrences, and the small past-producing mine (labeled "Unknown") lie within about 150 m of section from approximately the bottom of the Farson Member to the upper part of the Cathedral Bluffs Tongue (Zeller and Stephen, 1969, plates 1 and 2; and figure 29, this report). Once more, subsurface information from drill holes in this area and extending south in a fence into the Big Sandy block are needed to better measure the potential for sandstone roll-front uranium deposits beneath the proposed withdrawal area.

The Fontenelle block has more strong signals of major ferric-iron minerals in outcrops than any of the other examples (fig. 32). Although there is strong evidence for the presence of ferric-iron minerals from Landsat 7 data in the Fontenelle block, there is no reason to suggest that any of it is from sandstone uranium roll-front alteration. In the north-central part of the block, narrow bands of pixels showing the signature of abundant ferric-iron minerals run directly along the east-trending valleys; but these patterns conform with the drainage, not the bedding of the rocks, suggesting that this signal is from dry cheatgrass or other vegetation. In most places the major ferric-iron minerals signature is stratabound, but its strongest expression is in the Laney Member of the Green River Formation, which is mostly composed of oil shale and is an unsuitable host for sandstone-hosted roll-front uranium deposits. Additional stratabound anomalies are within the Wilkins Peak Member of the Green River Formation, in basal parts of that section that consist of oil shale. The stratigraphically lowest part of the Wasatch and Green River Formations is a basal conglomerate (unit Twco on fig. 32) followed upward by the La Barge Member of the Wasatch Formation, which would now be correlated with the main body of the Wasatch to the east and north. Both the basal conglomerate and the main body of the Wasatch are red beds, and the hematite that colors the red beds is the source of their patchy strong ferric-iron minerals signature in the spectral data from Landsat 7 imagery. Between the main body of the Green River Formation and the base of the Wilkins Peak, Roehler (1991) has described the Farson Sandstone Member of the Green River Formation and the overlying Alkali Creek Tongue of the Wasatch Formation, both sandy intervals, and both apparently unaltered with only drab-colored sandstones, some of them calcareous. The Cathedral Bluffs Tongue of the Wasatch was the other interval with some potential to the north, and it must correlate with the upper part of the Wasatch, unit Twu of M'Gonigle and Dover (2004). In that interval, as well, Roehler (1991) describes only drab-colored sandstones until near the top of the interval, where, instead, he describes rocks of the red muddy facies that cannot be mineralized because they are already oxidized.

In the Fontenelle block (fig. 32), the Wasatch Formation crops out in hogback ridges near the western boundary of the block, parallel to the underlying Hogback thrust fault, and the rocks dip eastward into the subsurface, with dips flattening to the east. To the east, like the area north of the Big Sandy block, the Laney Shale Member of the Green River Formation appears above the Wasatch Formation. There are no past-producing uranium mines in the study area, nor to the west in recharge zones for Wasatch aquifers. There are no uranium mineral occurrences in the proposed withdrawal area or the recharge areas. There is no pattern of airborne gamma-ray spectrometry anomalies from NURE data. There are no uranium anomalous geochemical samples for this area in USGS archives. There are no active claims for uranium. There are closed lode claims in sections 2 and 3, T. 24 N., R. 114 W. (fig.17), but these are not in the proposed withdrawal area.

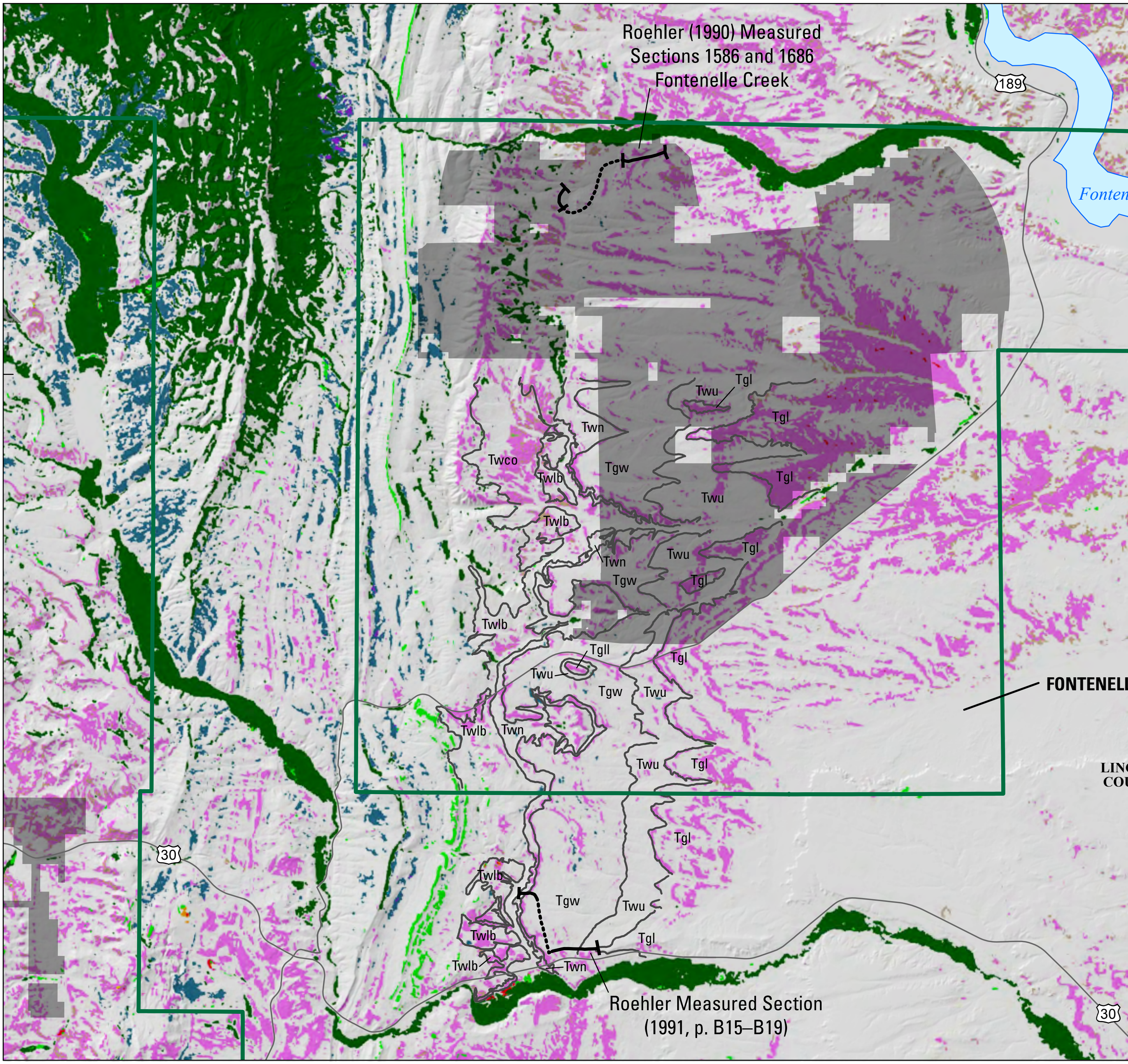
### Exploration and Mining Activity

The nearest known sandstone roll-front uranium deposit to the Continental Divide block lies about 56 km east-northeast and is called Bison Basin (Dahlkamp, 2010, p. 182 and p. 192–193). Additional small roll-front deposits lie to the west of that and as near as 40 km east of the Continental Divide block. Drilling may have penetrated roll fronts nearly as far west as Oregon Buttes (Bill Boberg, oral commun., April 29, 2016); an occurrence also indicated, but not fully documented, by Childers (1974, p. 138).

At present, there are no active uranium claims and no pending or authorized plans for surface disturbance related to uranium mining or exploration in any of the Big Sandy, Continental Divide, Fontenelle, or Boars Tusk blocks. There are closed lode claims in section 26, T. 27 N., R. 105 W., and in section 29, T. 26 N., R. 106 W., of the Big Sandy block (fig. 17). It is not known if uranium was the intended target of those claims.

### Potential for Occurrence

A tract for evaluation of potential for sandstone roll-front uranium deposits in the South Pass, Big Sandy, and Continental Divide blocks was constructed as follows. The north boundary of the tract is the Continental Fault across the northeastern corner of the Big Sandy block (fig. 33). (Wasatch Formation rocks probably exist north of the Continental Fault, but sandstone roll-front uranium deposits are not known to occupy such a position at any other place in the State, relative to a thrust fault bounding a Wyoming range.) South of the fault, the Wasatch Formation crops out between the fault and the places where, farther south, the Wasatch is overlain by the Laney Shale Member of the Green River Formation. Rocks prospective for sandstone roll-front uranium deposits

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Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
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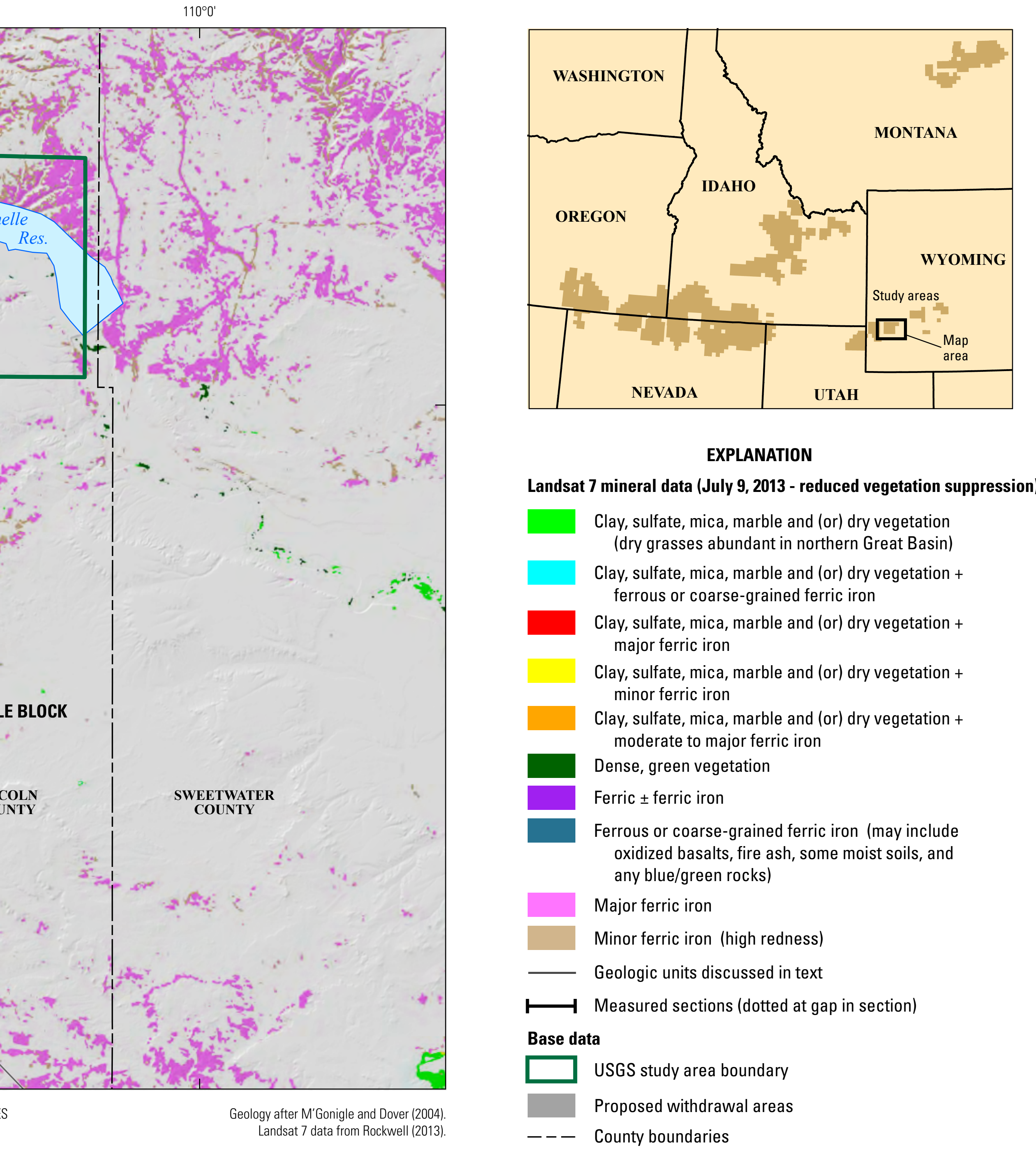



**Figure 32.** Map showing Landsat 7 spectral mineral signatures from the intertongued Wasatch and Green River Formations in the Fontenelle block, Bear River Watershed study area, Wyoming, and their relation to sandstone roll-front uranium system alteration. Formation contacts are from M'Gonigle and Dover (2004). Correlations of their units with those of Roehler (1991) are as follows from the base of the Wasatch Formation on the west: Twco—Wasatch Formation basal conglomerate; Twlb— La Barge Member of the Wasatch Formation, which is equivalent to Roehler's main body of the Wasatch; Twn—New Fork Tongue of the Wasatch Formation, which is equivalent to, in ascending stratigraphic order, Schegg's bed of the Green River Formation of Roehler (1991), Farson Sandstone Member of the Green River Formation, and Alkali Creek Tongue of the Wasatch Formation; Tgw—Wilkins Peak Member of the Green River Formation; Twu—upper Wasatch Formation, which is equivalent to Cathedral Bluffs Member of the Wasatch; Tgl—Laney Member of the Green River Formation.

are sandstones down section from the Laney within the upper, Cathedral Bluffs Tongue of the Wasatch and, underlying those, the sandstones of the Farson Sandstone Member of the Green River Formation. Sandstones in both those intervals should be present in the subsurface below both the Continental Divide and the Big Sandy PLSS blocks. That is, to the best of our knowledge, potentially favorable host rocks underlie both proposed withdrawal areas.

The tract has been artificially confined to the west and east, as follows. From the northwestern corner of the Big Sandy block and the southeastern corner of the Continental Divide block, lines were drawn perpendicular to the trace of the Continental Fault about 8 km to the west of the line on the west edge of the Big Sandy block and about 8 km to the east of the line on the east of the Continental Divide block to the South Pass block. Those lines were extended far enough southward to enclose the entirety of the Big Sandy and Continental Divide PLSS blocks, and a line parallel to the Continental Fault was then extended from west to east from the southeast end of the Continental Divide block to meet the end of the eastern boundary (fig. 33).

The potential for sandstone roll-front uranium deposits in the South Pass, Continental Divide and Big Sandy blocks must be greater than “low,” because there is evidence of uranium mobility in the assumed recharge areas of the Wasatch and Green River Formation sandstones up gradient from the proposed withdrawal area. Evidence for uranium deposits is in the form of radioactive anomalies identified on the ground by Winterhalder (1954), the small past-producing uranium mine, and possible sandstone roll-front-system alteration (fig. 29). However, through most of the area of this hypothesized recharge area, there is no suggestion of sandstone roll-front uranium system alteration particularly in comparison to areas that have known altered rocks in outcrop. Possible outcrops of altered rock occur near Winterhalder’s (1954) radiometric anomalies numbers 3 and 2, respectively (fig. 29). These are in what probably was the recharge area for Cathedral Bluffs and Farson Member sandstones that then extended south beneath the Big Sandy block. However, because of the vagaries of groundwater movement directions in the subsurface and our lack of knowledge of the paleo-geography during the (geologic) time when mineralizing processes might have occurred, the Continental Divide block might have equal or higher potential than the Big Sandy block. The potential rating for this tract (fig. 33) is considered to be moderate (M), given the evidence for uranium mobility (fig. 29). The certainty level is B, because we currently have no drill hole data from the study area, and the evidence is indirect, based only from the hypothesized recharge area to the north near the Continental Fault (fig. 29). With further drill hole data, the potential and certainty levels potentially would be modified.

The Boars Tusk block appears to have no potential for sandstone roll-front uranium deposits because the Farson Sandstone Member crops out west of the two PLSS townships containing proposed withdrawal areas, and crops out at higher elevation than either township, and dips westward away from the proposed withdrawal areas. Therefore, Farson Member host rocks aren’t present beneath the Boars Tusk block. The Cathedral Bluffs Member, if present, lies above the Farson so also is not present beneath the study area. The only Wasatch rocks that may underlie the Boars Tusk block, itself, is the main body of the Wasatch Formation, and it is likely to be the muddy, red-bed facies at the bottom of Roehler’s (1990) measured section and thus not prospective for sandstone roll-front uranium deposits.

Potential for sandstone roll-front uranium deposits in the subsurface of the Fontenelle block is rated low (L). There is no evidence for any mobility of uranium in this area, nor, particularly, in the recharge areas for Wasatch or Green River sandstones on the western edge of the block. However, there are suitable host rocks—for example, the Farson Sandstone Member of the Green River Formation as measured by Roehler (1990) and described by Roehler (1991, p. B16–B19). Roehler described all of the sandstones of his Alkali Creek section, from both the Farson Member and the Alkali Creek Member, as being brown, gray-green, or gray. These descriptions suggest that there are no outcrops of roll-front alteration within the section. Given that suitable host rocks are present, but that there is no evidence for any uranium mineralizing process in the area, the potential is judged to be low (L). This potential rating is applied at certainty level C (fig. 33). The sandstones that are suitable host rocks can be observed in outcrop, and they appear to be unaltered, which is a piece of direct evidence that appears to refute the possible existence of uranium resources. Otherwise, there is simply an absence of any indications of mineralization processes for uranium.

### Economic Analysis

Any sandstone roll-front uranium deposits found in the subsurface below the Big Sandy, Continental Divide, or Fontenelle blocks are most likely to be produced by mining. There are operating mines of that type at the Crow Butte Mine near Crawford in western Nebraska and at the Highland Mine within the southern Powder River Basin, Wyoming, north of Douglas. In such mining, the surface disturbance is relatively small. There is no company activity to indicate any current interest in the area.

Further discussion of where uranium is being produced in the Western United States can be found in Bleiwas (2016).

## Surficial Mineral Deposits System, Including Placers

Ore depositing systems from the Earth’s surface include chemical and mechanical types. The most familiar chemical types are deposits formed as soils such as laterites and bauxites, for iron and aluminum, respectively. The mechanical types include placer deposits, that is, concentrations of valuable heavy minerals that fell from suspension in a transporting medium, typically moving water.

A placer deposit is a concentration of valuable detrital minerals formed by a process of sedimentation in which the relatively high specific gravity of the valuable minerals causes them to drop from suspension by the transporting medium and thereby separate from minerals of lower specific gravity that remain in suspension, or causes them to stop moving in a traction flow while the minerals of lower specific gravity continue with the flow.

Alluvial placers form in rivers and streams and represent the initial downstream concentration of heavy minerals relative to source rocks, within a watershed. Heavy minerals deposit and concentrate where gradients flatten and (or) where water flow velocity decreases (Yeend, 1986). “Heavy mineral grains are most concentrated at the base of gravel where natural traps such as riffles, fractures, bedding planes, or other features are oriented transverse to the water flow such as at the inside of meanders, below rapids and falls, beneath boulders, and in vegetation mats” (Jones and others, 2015, p. 25).

Minerals concentrated by this placer-forming process include native gold (Au) and other native metals, ilmenite ($FeTiO_3$), cassiterite ($SnO_2$), rutile ($TiO_2$), zircon ($ZrSiO_4$), monazite ((Ce,La,Th,Nd)$PO_4$), xenotime ($YPO_4$), and many others.

### Mineral Description

In placer deposits, the action of moving water or wind creates segregations of minerals of high density that are resistant to abrasion and resistant to breakdown by chemical and mechanical action. Concentration occurs in gravity traps such as depressions into bedrock on the bottoms of stream channels, or downstream from any feature that might be centimeters higher on the bed of a stream and lying transverse to the flow direction. A second potential setting of concentration is on beaches within the intertidal zone, referred to as the swash zone or the upper foreshore. There, the crashing waves wash all the sand grains up the slope of the beach, but the return of the water down the slope (the backwash) carries lighter minerals high in a millimeters- to rarely centimeters-thick sediment-charged flow while the denser minerals are left behind, the densest at the top of the wave’s reach and incrementally lighter minerals in their order towards the bottom of the beach. Each backwashing wave thus produces a lamination that has denser and typically finer-grained minerals at the bottom and lighter and coarser grained minerals at the top (Clifton, 1969). Because many of the dense minerals are dark colored, these placer deposits are sometimes referred to as black-sand deposits. Houston and Murphy (1977) determined that many of the heavy-mineral sand deposits from coastal environments in Wyoming formed in beach swash-zone environments. However, Force and Rich (1989) concluded that the Trail Ridge, Florida, heavy-mineral sand deposit formed in a back-beach eolian (wind-deposited) environment. Yet other black-sand deposits are believed to represent other depositional environments at or near a coastline (Roehler, 1989). A variety of near-the-coast depositional environments appear to be able to concentrate heavy minerals into economic concentrations.

### Geology and Occurrence in the Study Area

Stream placer-gold concentrations of two (or more) ages occur in and near the South Pass proposed withdrawal area. The older placer deposits are of early Eocene age within the Wasatch Formation. They occur partly within the South Pass block but outside of the proposed withdrawal area. The placer occurrences are just 1.1 km (0.67 mi) south of the proposed withdrawal area at the nearest point (fig. 34). A younger group of placer deposits occurs within Quaternary gravels, mostly in the alluvium along the modern streams. However, any Quaternary terrace gravels are also included in the tract for Quaternary placers.

In addition, heavy-mineral sands that formed in coastal environments may occur in the study area. One such deposit, near Cumberland Gap (Houston and Murphy, 1962), is 26 km (16 mi) south of the southeastern corner of the Fossil Basin block. Given their stratabound and stratiform nature, their relatively large areal extents (the best exposed of any of them in Wyoming is an elongated lens at least 4 km (2.5 mi) long, 180 m (600 ft) wide, and 3.7 m (12 ft) thick in the center; Houston and Murphy, 1977, p. A24), and with the continuity of the hosting sandstones across the study areas in the subsurface, heavy-mineral sand deposits are likely underlying a number of places in the Fossil Basin, Fontenelle, and Big Sandy blocks. Such deposits may also underlie the Boars Tusk and Continental Divide blocks. If the proposed withdrawal areas were larger in the Boars Tusk and Continental Divide blocks, they would certainly also contain heavy-mineral sand deposits locally.

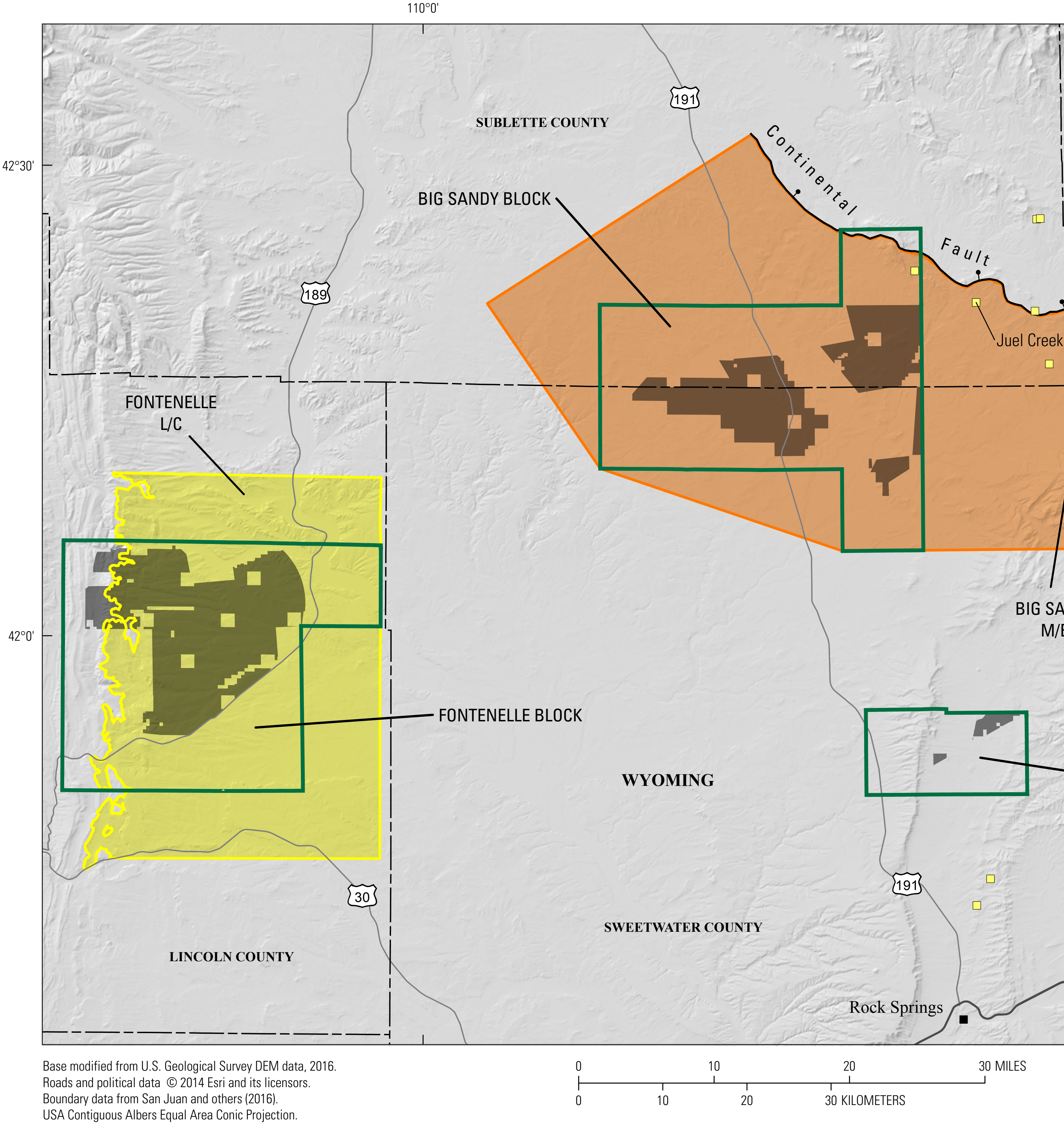
Each of these three types of placer deposits is addressed below, and tracts are evaluated for the first two types.

#### Paleoplacer Gold Deposits in the Study Area

*Geology and Occurrence in the Study Area.*—Placer gold concentrations of early Eocene age within the Wasatch Formation are partly within the South Pass block though outside of the proposed withdrawal area. The placer occurrences are 1.1 km (0.67 mi) south of the proposed withdrawal areas at their nearest points (fig. 34).

The Dickie Springs-Oregon Gulch area (fig. 34) has been mined in very small operations since 1863—even before the opening of the South Pass-Atlantic City district to its north—yet it has never supported anything but hand operations. Mining in this district has been difficult since the outset. The gold appears to be disseminated finely through large thicknesses of the conglomeratic facies of the Wasatch Formation, and, except seasonally, there is no supply of water for washing out the gold. Hausel (1980, p. 6) estimated that the Dickie Springs-Oregon Gulch “district” had produced 310,000 troy oz of gold by about 1926.

Gold in the Dickie Springs-Oregon Gulch paleoplacer district is hosted by cobble- to boulder-facies conglomerate of the lower Eocene Wasatch Formation, south of the Continental

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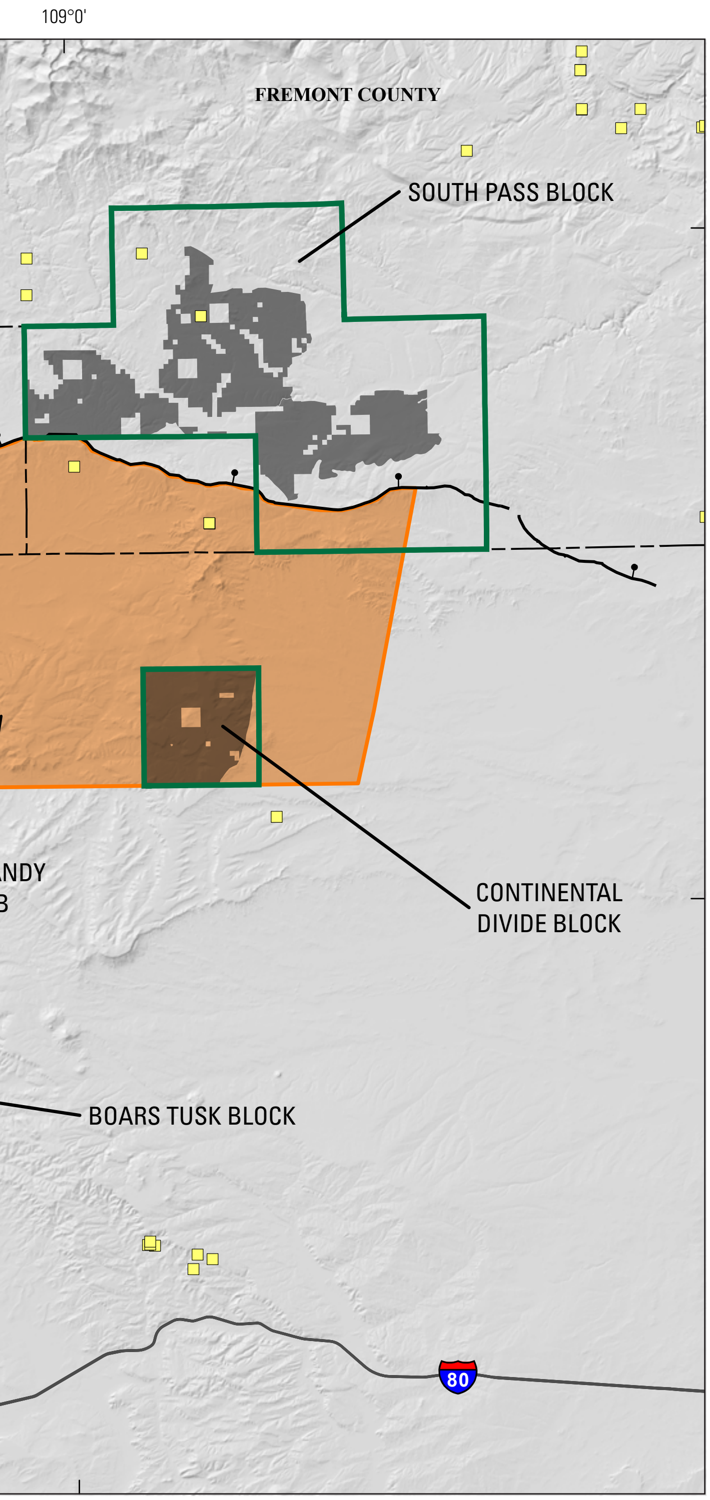
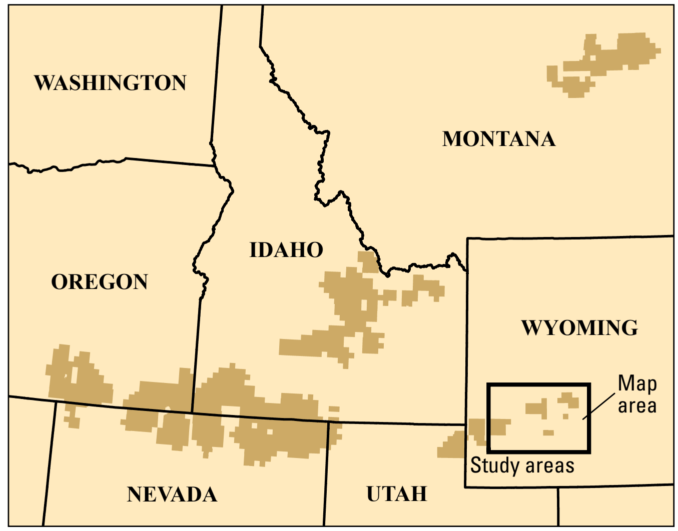
Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 110° W., latitude of origin, 37.5° N.
North American Datum of 1983.




Fault data from Sutherland and Hausel (2006), and Sutherland and Luhr (2011).
MRDS mine locations from USGS (2016).




**EXPLANATION**

**Assessment tract types – sandstone roll-front uranium**

Moderate-potential (M) tract with low (B) certainty

Low-potential (L) tract with moderate (C) certainty

**Geologic structure**

Continental Fault (ball and bar on downthrown plate)

**MRDS locatable minerals**

Uranium location

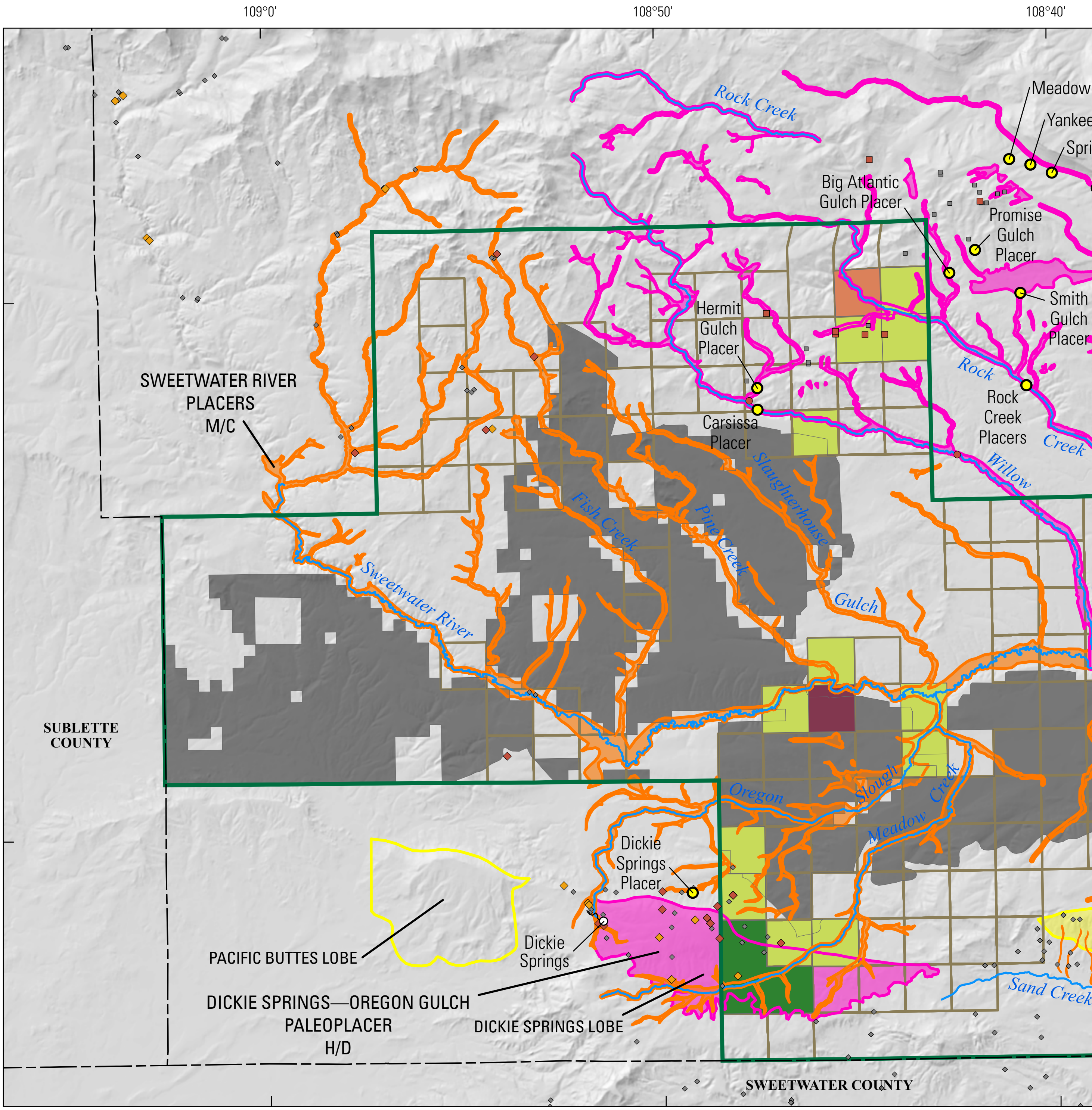
**Base data**

USGS study area boundary

Proposed withdrawal areas

County boundaries

**Figure 33.** Map showing mineral-potential tracts for sandstone roll-front uranium deposits in the Southwestern and South-Central Wyoming and Bear River Watershed study areas, Wyoming and Utah. USGS, U.S. Geological Survey. MRDS, USGS Mineral Resources Data System.

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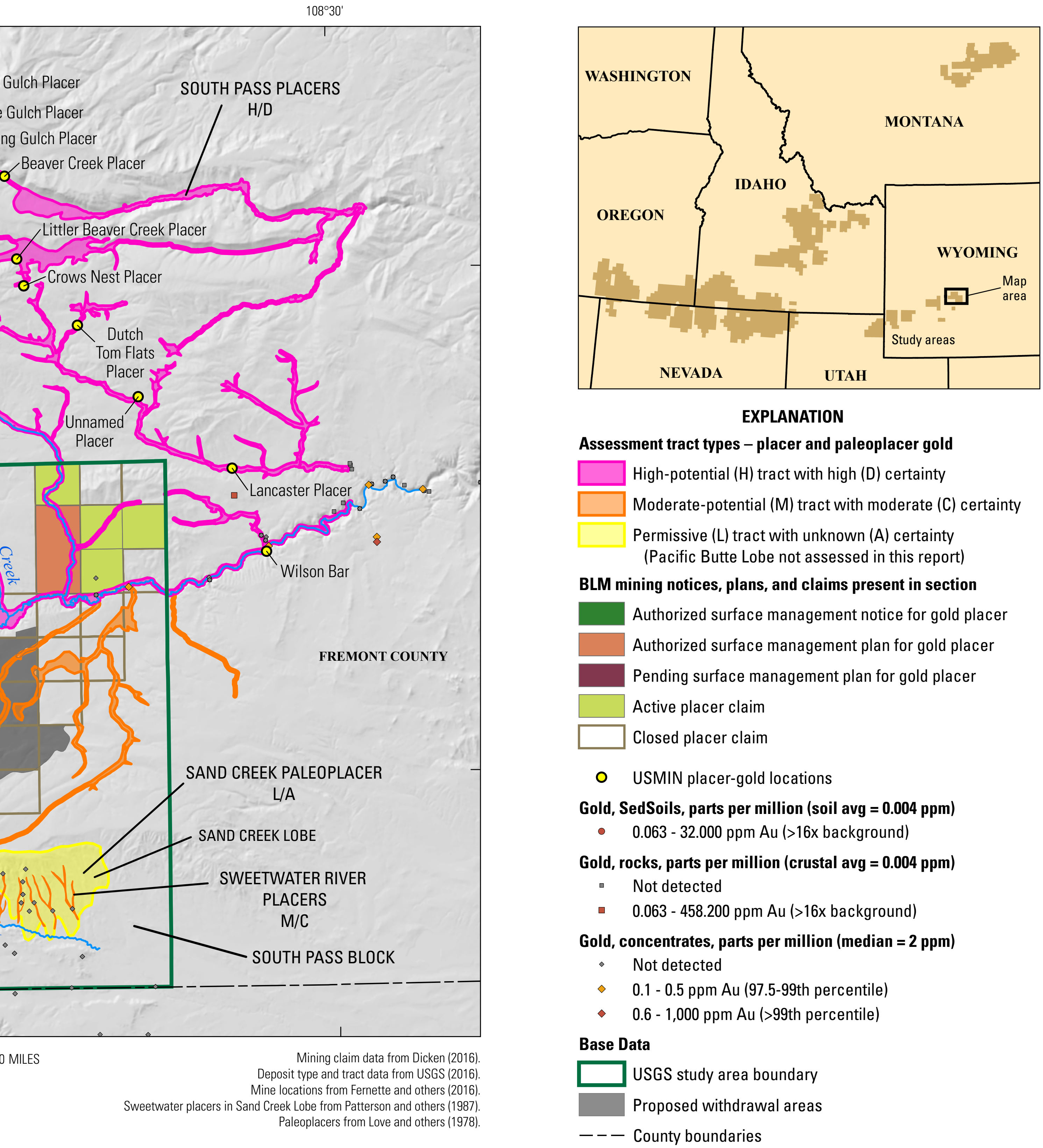


**Figure 34.** Map showing mineral-potential tracts for paleoplacer gold and placer gold in the South Pass block of the Southwestern and South-Central Wyoming study area, Wyoming. BLM, Bureau of Land Management; USGS, U.S. Geological Survey; USMIN, USGS Mineral Deposit Database.

Fault. The productive area's south boundary is formed where the Bridger Formation overlies the Wasatch on the south. The Wasatch conglomerate facies occurs in three or more lobes. These are the Pacific Butte lobe on the west (not shown on figure 34 as it is west of the study area, but still in Fremont County), the Dickie Springs lobe in the middle (Love and others, 1978), and the Sand Creek lobe on the east (Patterson and others, 1987) (fig. 34). The Dickie Springs lobe represents no less than 400 m (1,300 ft) in thickness of Wasatch section (Love and others, 1978), and the other lobes must also represent substantial thicknesses. Largely random sampling of the Pacific Butte and Dickie Springs lobes has yielded gold grades from below the level of detection up to 660 milligrams of gold per cubic meter of gravel (mg/m$^3$). However, that high end of the grades is subject to question because Love and others (1978) may not have ensured the validity of their results by processing bulk samples. Sample sizes in such sediment must be very large—on the order of a backhoe bucketful, rather than a 4.5-kilogram (10-pound) sample bag full—because the boulders must be mined along with the black sand.

If water were readily available, a dredging operation would require an average grade of no less than 500 mg/m$^3$ for profitable operation (J.F. Hayes, placer mining engineer with more than 25 years of experience, written commun., February, 2016). Only 1 of the 31 samples analyzed by Love and others (1978) from the Dickie Springs lobe contained greater than 500 mg/m$^3$ of gold, and only 5 of 31 samples even exceeded 100 mg/m$^3$ of gold.

*Exploration and Mining Activity.*—Placer claims continue to be held in the Dickie Springs conglomerate lobe, but none are found within either the Pacific Butte or the Sand Creek lobes. The Dickie Springs conglomerate lobe includes parts of 17 sections, and just 4 of those sections have active claims within them. The four sections directly overlie the Dickie Springs proper in Oregon Gulch. Mining in both areas may be focused on Quaternary sediments that overlie the Wasatch Formation rather than deposits in the Wasatch Formation. There is an authorized surface-management plan for placer gold mining within sections 19, 29, and 30, T. 27 N., R. 100 W. (fig. 17), covering three of the same sections that contain active placer claims along upper Oregon Gulch. These sections lie just south of the southern-most part of the proposed withdrawal area, and do not overlap it.

Fremont Gold U.S. LLC proposed and conducted placer gold exploration between 2005 and 2012 (Kirk Rentmeister, oral communication, June 7, 2016), in an area that they and the BLM referred to as the Dickie Springs project, but the actual work areas all lay north of the Continental Fault, thus involving no rock of the Wasatch Formation conglomerate lobes (Bureau of Land Management, 2005).

*Potential for Occurrence.*—As demonstrated by the many years of sporadic small-scale mining and the sampling results of Love and others (1978), there is certainly some demonstrable level of placer gold concentration in the Dickie Springs lobe of the Wasatch Formation conglomerate facies. The results of Love and others (1978) constitute a valid geochemical anomaly. Love and others (1978) even showed a picture of gold recovered by panning, thereby providing direct evidence for the presence of gold. Thus, although the grades cannot be interpreted to indicate a deposit with clear economic potential, the BLM classification of levels of potential requires this area to be classified with high (H) mineral resource potential for placer gold (fig. 34). A reminder is given that this does not imply that the potential concentration is or may be economic. Historically, the Dickie Springs lobe did produce gold. For that reason only, its certainty is rated at level D.

In contrast to the Dickie Springs lobe of Wasatch conglomerate facies, in the Pacific Butte conglomerate lobe to the west, all 11 samples analyzed contained less than 100 mg/m$^3$ of gold. Love and others (1978) describe the detrital composition of the Pacific Butte lobe, and it clearly had a different source area or areas than the Dickie Springs lobe. There appears to be no reason to consider the Pacific Butte lobe as a permissive tract at all, so we have not.

The Sand Creek lobe of Wasatch conglomerate facies was mapped and sampled by Patterson and others (1987). They state that the conglomerates there are gold bearing and show locations of eight samples from which native gold was found in panned concentrates (Patterson and others, 1987, plate 1). However, their text (Patterson and others, 1987, p. 11) states that 10 samples had native gold in the panned concentrates. A later section (Patterson and others, 1987, p. 17) states that, "Additional sampling of Quaternary alluvium and of conglomerate of Tertiary age showed that 5 of 28 samples of alluvium contained one or more gold flakes, but none of the 7 samples of Tertiary conglomerate yielded any gold." No gold geochemical analyses were provided for the whole rocks of any of these samples. They rated the lower Eocene conglomerates as having low resource potential at certainty level C (Patterson and others, 1987, plate 1) but rated seven tiny drainages with Quaternary sediments in them that drain the Sand Creek lobe as moderate (M) potential at level C certainty. There are no active claims in the area of the Sand Creek lobe, and there is no history of claims in that area. There are seemingly contradictory statements in Patterson and others (1987) about sampling results in the Sand Creek lobe of Wasatch conglomerate facies, so it is left to the reader to interpret what data are accurate and what are not. The rating applied by Patterson and others (1987) is consistent only with the descriptions that follow the early reconnaissance given on page 11. There, it stated that (after finding gold in panned concentrates in the reconnaissance phase), ". . . 5 of 28 [new] samples of Quaternary alluvium had flakes of gold in panned concentrates, but none of seven samples of Eocene conglomerates yielded gold in panned concentrates." They then rated the Quaternary alluvium to have moderate potential and the Eocene conglomerate to have low potential. We arrive at the same conclusion—that potential within the Sand Creek lobe of Wasatch conglomerate facies is low (L). The data are very sparse, but the most significant indicate that these conglomerates are along-strike equivalents of the Dickie Springs lobe—an indirect criterion.

Actual sampling results that can be reliably placed in time and space were all negative for the Tertiary conglomerates, as in the quotation above. The indicated certainty level really appears to be A: simply insufficient.

*Economic Analysis.*—Dickie Springs lobe of Wasatch conglomerate facies has a long history of producing small amounts of gold. To date, however, there appears to have been no valid test of the potential for economic mining in these rocks. Gold prices have been relatively stable for several years at a level that cannot be viewed as lucrative. The results of Love and others (1978) do not serve well as a valid test of the potential, as they did not take bulk samples; their samples were instead taken in 25- by 40-cm bags, each weighing about 11 pounds (p. 385). A valid test of this deposit remains to be completed.

Discussion of where gold is being produced in the Western United States can be found in Bleiwas (2016). No gold is currently produced in Wyoming, and none of the current gold production attributed to Utah is from the study area.

### Quaternary Placer Gold

Numerous placer claims continue to be held in the greater South Pass Quaternary placer area, and there are patented placer claims in many drainages. Some of the drainages are considered to be "mined out," but there may still be "colors" remaining. For the purpose of this report, we refer to all the Quaternary placer deposits in this area as the Sweetwater River placers (appendix 2).

*Geology and Occurrence in the Study Area*.—With somewhat greater reliability than his statements about production from the Dickie Springs-Oregon Gulch paleoplacers, Hausel (1991, p. 30–31) tabulated placer production of the South Pass-Atlantic City district, totaling 101,250 troy oz of gold from 8 placer mines. Hausel further gave his opinion (p. 64) that production for the dredging of Rock Creek between 1933 and 1941 is considerably underreported. There is little doubt that placer production from the earliest years of the district went entirely unreported. Among the areas having the largest placer production are Meadow Gulch (50,000 troy oz), Yankee Gulch (25,000 troy oz), and Rock Creek (at least 11,500 troy oz) (fig. 34).

There is a single pending surface management plan for placer gold in section 28, T. 28 N., R. 100 W. (fig. 17), at the confluence of Pine Creek with the Sweetwater River. Most of this section is included within the South Pass proposed withdrawal area, but the land immediately adjacent to the Sweetwater River that is probably an east-west line of four placer claims, is not. In that section there is a single active placer claim. There are also 8 closed placer claims and 38 closed lode gold claims in the section.

There is a single surface-management plan for placer gold mining that is authorized within the heart of the lode mining area in sections 2 and 11, T. 29 N., R. 100 W. (fig. 17). This is within the study area but is 8 km (5 mi) from proposed withdrawal area. Another surface management plan for placer gold mining is authorized on lower Rock Creek for the 3.2 km (2 mi) above its confluence with the Sweetwater River. This area is within the study area and lies 1.6 km (1 mi) northeast of the southeastern part of the proposed withdrawal area. Rock Creek above this area was all dredged between 1933 and 1941.

In the 8-section area that lies within the study area but outside of any proposed withdrawal area, and which constitutes somewhat more than half of the area with most of the lode gold mining, there are 7 active placer claims and 47 closed placer claims. That count does not include the area immediately surrounding South Pass City where many patented placer claims were apparently purchased and "segregated from mining" (Layman, 2012, p. 38). Conservatively estimated, as of a 1972 map (Bureau of Land Management, 1972), it appears that there were no fewer than 26 other patented placer claims or claim blocks or other once-private properties that have been "segregated from mining" across the principal area of lode mining in the South Pass-Atlantic City district.

*Potential for Occurrence.*—Considerable placer mining has taken place along drainages in Quaternary alluvium and other sediments within and downstream from the South Pass-Atlantic City gold district. Nonetheless there are large areas of drainages in the area remaining unmined. A notable one, for example, is Willow Creek below South Pass City. Examination of production records suggests that placer gold mining prospects can be divided into two levels of potential. Streams that directly drain the area of lode mines and have not been previously mined can all be considered direct extrapolations of those drainages already profitably mined. These are shown in bright pink on figure 34 as the South Pass placers. They are considered to have high (H) potential with a D level of certainty. Just as for the Dickie Springs lobe of lower Eocene conglomerate, the Quaternary gravels along the stream courses produced gold, and thus automatically get the certainty rating D.

Among the additional streams that drain lands without any lode gold mining, there are a number that nonetheless did support some placer mining. Included are Oregon Gulch-Meadow Creek and Dickie Springs Creek, which drain the Dickie Springs lobe of Wasatch conglomerate facies. Also included are drainages like Slaughterhouse Gulch, Pine Creek, and Fish Creek whose courses are marked by lines of patented placer claims. Together, all of these drainages are shown on figure 34 as the Sweetwater River placers. Historical production from these was minor, but some gold was recovered, leading to a rating of moderate (M) potential at certainty level C. The lines of patented placer claims along several streams rated in this category are direct evidence that a mineral resource probably exists, but the lack of production records and the lack of dredge tailings along the stream courses makes the presence of the claims only quantitatively minimal. Patterson and others (1987) assigned M/C to both these and the Quaternary alluvial placers, apparently assuming that the placer resource had been mostly exhausted.

*Economic Analysis.*—Discussion of where gold is being produced in the Western United States can be found in Bleiwas (2016). No gold is produced in Wyoming, and none of the current gold production attributed to Utah is from the study area.

### Coastal Titanium Placer Deposits

*Geology and Occurrence in the Study Area and Exploration.*—Coastal placer titanium (±zircon, ±rare-earth element) deposits, also called heavy-mineral sand deposits from coastal environments (VanGosen and others, 2014), almost certainly exist in the subsurface of the Big Sandy, Fontenelle, and Fossil Basin blocks. The same would be true of the Continental Divide and Boars Tusk blocks if they were larger, but those are relatively small areas. Within the Bear Lake Plateau block, it has not been demonstrated that Upper Cretaceous sandstone is present in the subsurface in thrust plates deep beneath the Lakeview-Meade Plate.

Heavy-mineral sand deposits are well known and widespread in Upper Cretaceous sandstones in Wyoming (Houston and Murphy, 1962) and elsewhere throughout the Rocky Mountain States (Houston and Murphy 1970; 1977; Force and Creely, 2000; Force and others, 2001). The Frontier Formation of earliest Late Cretaceous age, is host to a coastal placer titanium occurrence near Cumberland Gap about 26 km south of the nearest proposed withdrawal area in the southeast part of the Fossil Basin block.

In the Cumberland Gap area, the Frontier Formation represents the deposits of two progradations. In a progradation, sand is deposited and preserved beneath younger deposits as the beach and related deposits shift episodically seaward over thousands to tens of thousands of years. Bodies of coastal sand are overlain by estuarine coal, which is overlain by fluviatile sandstones and mudstones; progradation sequences contain sediment from continental environments over sediment that is marine. The two intervals of coastal and fluviatile rocks in the Frontier Formation are separated from one another by an interval of marine shale known as the Allan Hollow shale member (Hale, 1960). The shale was deposited during a westward transgression of the Late Cretaceous inland sea when the inland sea probably widened and became deeper. Transgression is the opposite of the beach prograding. During transgression, the beach and related deposits shift episodically continent-ward over thousands to tens of thousands of years. That entire cycle was apparently repeated a second time, with the top of the formation marked at the bottom of the transgressive beds of the second cycle, at the base of the Hilliard Shale. For a single place through all of Frontier depositional time, the coastal environments capable of creating a coastal titanium placer deposit passed over four times, first migrating eastward (by prograding coastal and fluviatile deposition), next moving westward (by marine transgression), then the same depositional environments repeated for the second progradation and transgression. However, Houston and Murphy (1970) observed that the black-sand deposits were associated only with the prograding parts of cycles, not with the transgressing parts, so for each place in western Wyoming when the Frontier Formation was being deposited there were two times within which heavy mineral sandstone deposits might form, namely the two times that beaches prograded across that place. At every time during the two progradations of the Frontier beaches, there was the chance, somewhere along the coastline, to produce a heavy-mineral sand deposit as part of the formation's sandstones. Although the exact position within the stratigraphy is not known, the likelihood of there being a coastal placer titanium deposit somewhere beneath an area as large as the Fossil Basin proposed withdrawal area is very high.

Beneath the Fontenelle, the Big Sandy, the Boars Tusk, and the Continental Divide blocks, everywhere at depths of at least one hundred meters (a few hundred feet), and at some places at depths of more than 1 km, the Rock Springs Formation of the Mesaverde Group may also contain heavy-mineral sand occurrences. In the Rock Springs Formation, there was first a transgression of the Cretaceous interior sea where it overrode and eroded a small amount of previously deposited rocks in what later became the Green River Basin, then progradation took the coastal sand-depositing environments back eastward across the same area. So for Rock Springs time, each location had one chance for a coastal placer titanium deposit to form.

Given a large enough area, the probability that there is a heavy-mineral sand deposit within the Rock Springs Formation somewhere beneath the study area in the Green River Basin is very high. The spacing to be expected at any given time is shown, for example, by Roehler (1989). Over the time of deposition of the McCourt Sandstone Tongue of the Rock Springs Formation of the Mesaverde Group, typically about 21 m thick, no fewer than six heavy-mineral sand occurrences formed along a 64-km long stretch of coastline (Roehler, 1989, p. 3). All together the six heavy mineral sand deposits occupied a minimum of 1,811 m of the McCourt coastline (Roehler, 1989, plate 1), which accounts for at least 2.8 percent of the total length of coastline and probably considerably more. Lengths of black-sandstone outcrop could be measured only in the direction along outcrop, probably only rarely in the actual direction of elongation of the black sandstone deposit; thus 1,811 m cumulatively along outcrop is a minimum total length of black sandstone deposits. The certainty that heavy-mineral sand deposits are present in the subsurface within any given large area is best understood with the analogy of crossing an area with a discrete groups of points along a line, as follows. The McCourt Sandstone coastline with 1,811 m of black sand being deposited in six groups of points per 64.4-km reach of coastline is viewed as crossing eastward across all of the southwestern quarter of Wyoming over perhaps 100,000 years of prograding and depositing the sand. During the crossing (progradation), each of the six segments that total 1,811 m in length, in each instant of time, shift slightly north or south along the coastline. The overall crossing produces an area of heavy mineral sand deposition by the combination of moving eastward across (progradation) and migration of a black-sand depositing environment along the line (coastline). The only uncertainty is whether each particular area and thickness of black sand is preserved, not eroded away just days or weeks later along the shifting coastline. Otherwise, every place where the McCourt sandstone is present would have greater than a 2.8-percent chance to have a coastal environment heavy mineral-sandstone deposit present; any vertical plane along the 64.4-km paleo-coastline is likely to have six black sand deposits present even after some were eroded away along the shifting coastline.

Looked at differently, if the McCourt Sandstone was everywhere at the surface, it should be a rare case to be able to move more than 12.45 km in any direction without encountering a McCourt-hosted black sandstone deposit. That 12.45 km distance is 64,390 m minus 1,814 m divided by 5—the 64 km length along outcrop minus the length of exposed (outcropping) black sandstone divided by the 5 intervals between the 6 black-sand deposits. Thus, 12.45 km is a very conservative figure because not all of the McCourt is outcropping along the entire 64 km—probably much less than 50 percent is outcropping—and, as before, where black sandstone is at the surface, the outcrop probably does not run along the direction of elongation of the body of black sandstone. With that result, it is clear why any land area of a township (6 miles by 6 miles, or 9.6 km by 9.6 km) is likely to have at least one McCourt-hosted black-sandstone body underlying it, and a block totaling 10 townships like the Fontenelle block is all but certain to have at least one.

However, modern heavy-mineral sand deposits from coastal environments are mined from sediment that has not yet lithified; the deposit is still a weak aggregate of nearly loose detrital grains, or the sediment has not even aggregated at all. Also, these deposits are at and immediately below the surface, accessible to open-pit mining. They can be mined without blasting, and the ore (sediment) fed directly into a gravity separation circuit—they do not need to be crushed or ground. Therefore, lithified sandstones of Wyoming's Late Cretaceous coastal placer titanium deposits cannot currently compete economically with the deposits along modern coastlines, nor will they be able to compete until almost all the heavy-mineral sands along the modern coasts are mined out. Furthermore, most of Wyoming's coastal placer titanium deposits are buried, requiring underground mining, and mining and extraction costs are far greater than in the loose sand deposits along modern or Pleistocene coastlines. Therefore, although the coastal placer titanium occurrences and deposits must almost certainly be present, they can be considered resources only for the long-term future, because they are not economically competitive with deposits along the modern coastlines that require no underground access, no drilling, no blasting, no crushing, and no grinding.

*Potential for Occurrence.*—Subsurface data is inadequate to try to further quantify the numbers of this type of deposit anywhere beneath the study area. However, with knowledge of the stratigraphic intervals that contain black-sand deposits, an oil well natural gamma log of an oil test has occasionally identified such a deposit in Wyoming. Anomalous concentration of, for example, monazite in the black sandstone produces a high-gamma zone within the known host sandstone interval. Petroleum tests, almost nowhere drilled any closer to one another than the next quarter-quarter of a section even within a producing field (660-ft grid spacing), never really test continuity of an accidently penetrated black sandstone deposit. It is beyond the scope of this work to check for natural gamma log anomalies within the Frontier Formation and the Rock Springs Formation in every petroleum test hole in every proposed withdrawal area. Therefore, no tract for assessment for coastal placer titanium deposits is drawn, and no assessments of resource potential are given for the Southwestern and South-Central Wyoming and Bear River Watershed study areas.

*Economic Analysis.*—As discussed above, heavy-mineral sand deposits in Upper Cretaceous sandstones in the study areas are not now economic, and they will not become economic until the heavy-mineral sand deposits along the world's modern coastlines are all exhausted or nearly so.

Discussion of where titanium is being produced in the United States can be found in Bleiwas (2016). There has been no production of titanium from the study area.

## Nonmetallic Locatable Minerals

No nonmetallic locatable minerals are found in the study area. Nevertheless, there may be potential for diatreme-hosted diamond deposits associated with lamproites of the Leucite Hills volcanic field and for high-purity dolomite principally in the Bear Lake Plateau block. Each is discussed briefly, below.

### Diatreme-Hosted Diamond (Diamonds in Lamproite)

#### Mineral Description

Diamond is a crystalline form of elemental carbon that forms at extremely high temperature and pressure conditions that are possible only deep in the Earth's upper mantle. Large diamonds, particularly large diamonds without flaws, are extremely rare and are very valuable as gemstones. The vast majority of diamonds, however, are small, flawed, and colored by various impurities. These small impure diamonds have a variety of industrial uses, particularly as abrasives to embed in saw blades for cutting stone and concrete, and are similarly used for core-drilling bits.

#### Geology and Occurrence in the Study Area

The Southwestern and South-Central Wyoming study area includes a single area with some potential for diamonds, namely the Leucite Hills volcanic field. The Leucite Hills are 22 occurrences of intrusive and extrusive lamproite scattered across about 960 km$^2$ (375 mi$^2$) of the northern part of the Rock Springs Uplift (fig. 35). Lamproites are rare, strongly alkaline, mafic to ultramafic, igneous rocks. Those of the Leucite Hills are ultrapotassic, containing major proportions of either leucite or sanidine together with phlogopite and diopsidic pyroxene.

Boars Tusk itself, a well-known landmark, is a two-spired volcanic neck that stands nearly 122 m (400 ft) high above the flood plain of Killpecker Creek. It is about 42 km (26 mi) north of Rock Springs. It is an erosional remnant of wyomingite; that is, phlogopite-diopside-leucite lamproite.

Lamproites are one of two types of igneous rocks that are known host rocks to diamonds. The other, more familiar igneous rock type associated with diamonds is kimberlite, and some igneous rock classifications divide a third rock type, orangeite, apart from kimberlites. Both lamproites and kimberlites are typically found in areas of thick crust and subcrustal lithosphere, commonly greater than 75 km (46 mi) thick. Both kimberlites and lamproites occur in fields or swarms that contain tens of individual small pipes or dikes of igneous rock, and the Leucite Hills are typical of such a field (fig. 35). Thick subcrustal lithosphere is typically present under old, Archean cratons, like the Wyoming craton. Lamproitic and kimberlitic magmatism requires such thick lithosphere because the temperatures at which such magmas form are greater than 1,200 °C and the pressures are 60 to 75 kilobars, corresponding to depths of 160 to 200 km below surface (Eggler and others, 1979). In addition, diamonds are only stable at depths greater than 150 km (Haggerty, 1999). The instability of diamonds from 150 km to perhaps 50 km depth has led geologists to conclude that they must move through that zone rapidly—perhaps even explosively—in small batches of kimberlite or lamproite magma, consistent with the abundant xenolith and xenocryst fragments in such rocks.

The igneous rocks of the Leucite Hills include a variety of lamproites but no kimberlites. They include several volcanic necks and a number of restricted-area (less than a few tens of square kilometers) volcanic flows, now expressed as erosion resistant cap rocks for small mesas. Boars Tusk and another lamproite occur north of proposed withdrwal areas in the northeast corner of the Boars Tusk block. The other intrusive body is the Matthews Hill dike. The next nearest known lamproite is at Twin Rocks, which is more than 11 km (7 mi) from the nearest proposed withdrawal area (fig. 35). Lange and others (2000) give a range of ages for the Leucite Hills of 3.0 to 0.89 Ma.

To date, all lamproites that are known to contain diamonds also (1) contain (forsteritic) olivine, (2) contain chromite (both of the above are xenocrytic or xenolithic, as are the diamonds themselves), (3) have greater than 20 percent MgO, (4) have less than 45 percent $SiO_2$, and (5) contain greater than or equal to 7 percent $K_2O$ (Scott-Smith, 1996). Where diamonds have been found in lamproites, they are restricted to volcaniclastic facies olivine lamproites and have not been found in intrusive olivine lamproites, even in the same igneous complex. Diamonds are not restricted to volcaniclastic facies of kimberlites.

In the Leucite Hills volcanic field, olivine has been found in 6 of the 22 lamproites—Endlich Hill, Hague Hill, South Table Mountain, Emmons Mesa, Hatcher Mesa, and Black Rock (Hausel, 2006, appendix 1). All six of those are in the eastern half of the volcanic field, not nearer than 12 km (9 mi) from any proposed withdrawal area. Chromite has not been reported in any lamproite in the field, to date. None of the 59 single-locality samples reported by Hausel (2006, appendix 2) contains more than 20 percent MgO. The highest MgO reported is 12.75 percent from Kuehner (1980), but the source of that sample is not available to us. The second-highest MgO is 11.75 percent (Kuehner and others, 1981, p. 671) in a madupite (diopside-bearing lamproite with high barium, strontium, thorium, and light rare earth elements, and low nickel; they may be differentiates of wyomingites or orendites [diopside-sanidine-phlogopite lamproite] but cannot be a differentiation parent to those others) from Pilot Butte. Eight of the 59 single-locality samples reported by Hausel (2006, appendix 2) had less than 45 percent $SiO_2$. Seven of those were madupites, and they came from a variety of places around the volcanic field, although several were from Pilot Butte and one was from Twin Rocks. One sample was a “transitional rock” (rock having some of the petrographic characteristics of both wyomingite and madupite and that contain analcime and other zeolites; probably they have been secondarily altered) from Twin Rocks. Seven of the 59 single-locality samples reported by Hausel (2006, appendix 2) contained less than or equal to 7 percent $K_2O$. All but one of those also had less than 45 percent $SiO_2$. All of the lower potassic rocks were either madupites or were aphanitic volcanics, and one was the same “transitional” (secondarily altered) rock as had the high $SiO_2$. Of the four poorly potassic rocks that were located, two were from Pilot Butte, and 2 were from Twin Rocks. In summary, a total of only 8 of the 59 sample analyses compiled by Hausel (2006, appendix 2) met even one of Scott-Smith’s (1996) petrologic or chemical criteria for diamond favorability. Five of those were from Pilot Butte and Twin Rocks, and did not also have olivine or green omphacitic pyroxene. Locations of the remaining three are not known. Thus, both mineralogical and chemical studies suggest the chances for diamonds in the known lamproites of the Leucite Hills are low at best. Only lamproites that are not yet breached by erosion can be considered prospective.

## Exploration and Mining Activity

Boars Tusk and the other lamproites of the Leucite Hills have been cursorily explored for diamonds. Both studies that have been published (Hausel, 2006; Chesner and others, 1998) mainly used the method of indicator minerals, which continues to be the industry standard. The method, developed first from kimberlites, takes a very large sample of soil or alluvial sediment, separates its heavy minerals, and searches them optically (typically with a binocular microscope) for minerals that have mantle origins. Indicators include pyrope garnet, pyrope-almandine, chromium-rich diopside, omphacitic (grass-green, aluminous) diopside, chromium-rich enstatite, chromite, and picroilmenite (Mg-rich) (Fipke and others, 1995). Hausel (2006) focused on indicator minerals in the

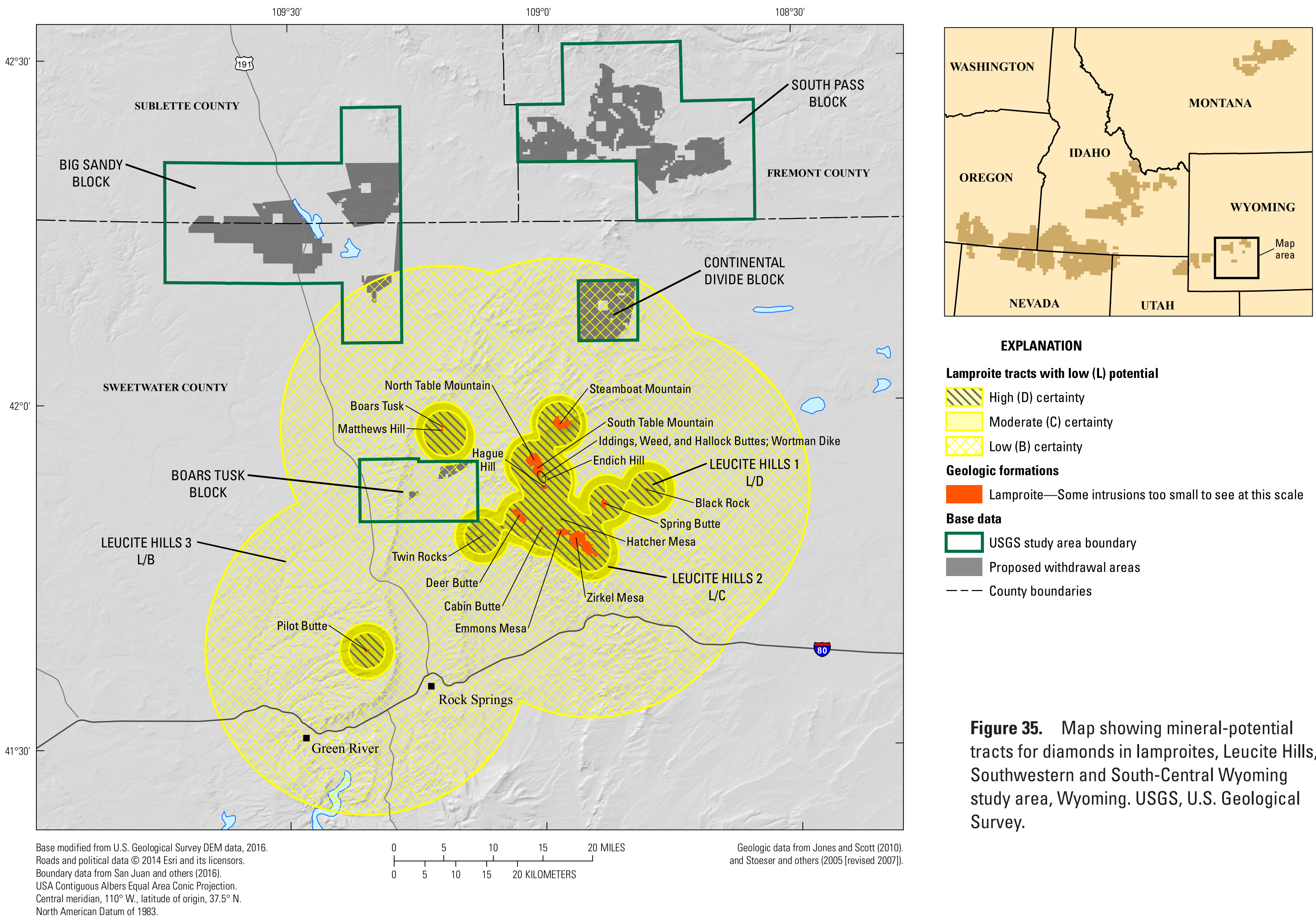


**Figure 35.** Map showing mineral-potential tracts for diamonds in lamproites, Leucite Hills, Southwestern and South-Central Wyoming study area, Wyoming. USGS, U.S. Geological Survey.

eastern part of the Leucite Hills, where olivine had been found as a xenocryst in six of the lamproite plugs and flows and where omphacitic diopside had been described earlier from the Hatcher Mesa flows (Barton and van Bergen, 1981). Thus, Hausel's work provided no test of the Boars Tusk or Matthews Hill volcanic necks for diamond. There was an assumption, probably a reasonable one, that none was justified. The other exploration using indicator minerals was reported in Chesner and others (1998). They started by documenting olivine in 10 of the 22 exposures of Leucite Hills lamproites, then focused on only those 10 for further work, again leaving out Boars Tusk and Matthews Hill (the 10 that have olivine are not named, and Hausel [2006], documents only 6 with olivine). These are such volumetrically tiny batches of magma that it may be reasonable to assume that the rock exposed is the only kind of igneous rock present near any one locality. Yet abandoning Boars Tusk and the Matthews Hill dike may not have been fully justifiable, because Fipke and others (1995) state clearly that the method is "not as successful when applied to lamproites [as opposed to kimberlites]." That is true, in part, because kimberlites can have orders of magnitude greater concentrations of the indicator minerals than lamproites. In the Argyle lamproite deposit in Australia, the largest and richest diamond deposit in the world to date, it has been observed that garnet is replaced by aluminous spinel and pyroxenes in what may equate to a retrograde reaction on the fall in pressure and temperature from mantle depths (Fipke and others, 1995, p. 60). If true generally for lamproites as opposed to kimberlites, the great difference in concentrations of indicator minerals could be explained. However, aluminous spinel has not been described from anywhere in the Leucite Hills.

It is not clear that indicator-mineral studies conducted by Hausel (2006) and by Chesner and others (1998) meet industry standards. Industry investigations typically collect samples of 40 kg (88 lb) or more and separate heavy minerals from the entirety of the large samples, commonly using a Wilfley shaking table. Only samples that large are considered sufficiently representative. Shipping such samples can be a major expense, so it is common to do the Wilfley table separations in the field so that only the separates of heavy minerals need to be shipped. Where possible, it is even a common practice to examine the heavy mineral separates in the field (Karl Smithson and James Austin of Southern Era Resources, Ltd., oral commun., July 7, 1998, near Mogoto, South Africa). It would be typical for exploration geologists using indicator minerals to specify in reporting that samples of 40 kg were collected and processed for heavy minerals. Neither Hausel (2006) nor Chesner and others (1998) reported the size of their samples, and Hausel reported conducting the separation of heavy minerals using a grease table rather than a Wilfley table (Hausel, 2006, p. 40).

### Potential for Occurrence

Fipke and others (1995, p. 2) states that "less than 1 percent of kimberlite pipes are sufficiently diamondiferous to be economic." A similar number probably applies also to lamproites. That fact, along with results from the five tests from mineralogy and geochemistry, suggest that it is unlikely that any buried intrusive bodies in the Leucite Hills volcanic field would contain diamonds, particularly at commercial grades.

Tract delineation is based on the tendency of lamproite/kimberlite intrusions (diatremes) and related rocks to occur in clusters. We used the distances between intrusions and intrusion density to create mineral potential tracts. Two Esri ArcGIS tools were used to construct the lamproite tracts (fig. 35): (1) the "Generate Near Table" tool (to compute the "maximum near distance"), and (2) the "Kernel Density" tool (Hammarstrom and Zientek, 2016).

First, the distance between the center (centroid) of every lamproite (pipe or neck, not including flows) was determined using ArcMap's "Generate Near Table" tool. The maximum near-distance is 26.4 km for the Leucite Hills lamproites (from Twin Rocks to Pilot Butte). We use this value as the *radius* from which to draw a boundary (buffer) around all the known lamproites. This boundary forms the outer extent of the tract with the lowest level of confidence (B). Second, in order to map areas with certainty levels C and D (see appendix 1), the kernel density surface (a raster file) was created in ArcGIS and classified into three groups using a geometrical interval classification scheme. For the Leucite Hills lamproites, the boundary between the D and C certainty levels ranges from 2,919 m to 4,093 m to the center of the nearest lamproite, and the boundary between the C and B certainty levels ranges from 4,417 m to 4,878 m to the center of the nearest lamproite. Only in the extreme southeast corner of the Boars Tusk block does the certainty reach level D.

Most of the lands of the Boars Tusk block are considered to have low (L) potential for diatreme-hosted diamond deposits with a B level of certainty. All of the Continental Divide block is also rated with the same level of potential and certainty (L/B). A relatively small part of the Big Sandy block is also considered to have low potential with B-level certainty. These large areas reflect a lack of knowledge on why the lamproites have intruded where they did and a lack of data to predict where more might be found. In known kimberlite fields, closely spaced lines of magnetic geophysical surveys have been effective in locating additional covered kimberlites. Lines spaced that closely serve only the purpose of exploration, and public-sector magnetic geophysical surveys are never so closely spaced.

Within the study area, a small part along the northern edge and another in the southeastern corner of the Boars Tusk block are the only areas considered to have any different level of certainty, although still at only a low level of potential. Those segments are rated with low (L) potential and level C certainty (fig. 35). Being as close to Boars Tusk and Matthews Hill lamproites as the northern segment is, the evidence is considered direct rather than indirect for there being some low level of potential for a diamond deposit in a lamproite that is not yet exposed by erosion. However, the evidence is still rather minimal. Moving closer yet to those lamproites, there is still not even moderate potential for a diamond deposit. After all, the various mineralogic and geochemical studies and the indicator minerals exploration efforts have given little evidence that these lamproites contain diamonds, yet the certainty increases nearer to a known lamproite. At the extreme southeast corner of the Boars Tusk block the potential barely skims the area rated Low (L) with certainty level (D).

### Economic Analysis

Once a diamond-bearing lamproite is found, there is still only a small possibility that there will be an economic concentration of diamonds in the lamproite, with the economics strongly affected by the number of gem quality diamonds as opposed to industrial diamonds. For the Leucite Hills, it probably is not appropriate to discuss economics unless or until a diamond is found.

## Dolomite

Dolostone is a sedimentary rock consisting of calcium-magnesium-carbonate that is more than 50 percent dolomite—$CaMg(CO_3)_2$. Carbonate rocks are used in gold mining operations, cement making, nutrition, agricultural, and other industrial applications (U.S. Geological Survey, 2004). Dolomite is generally less suitable than other industrial carbonates for most applications. Most dolomite that is mined is simply crushed and sieved for use as aggregate in concrete or asphalt (Bliss and others, 2008).

### Mineral Description

Dolostone, the sedimentary rock, is composed of calcium-magnesium carbonate, the mineral dolomite.

### Geology and Occurrence in the Study Area

Few dolomitic units are exposed in the western part of the Bear Lake Plateau block (fig. 6). The units include Jurassic Twin Creek Limestone at the extreme southern end of the block where there is a Utah Department of Highways potential gravel pit (Utah Mineral Occurrence System, UMOS, 1027; MRDS 10276517; USMIN 5351). No other pits or prospects are within this rock unit.

Little Creek Limestone Pit (UMOS 191; MRDS 10227074 and 10011446), also known as the Randolf Limestone Pit (USMIN), is a fossiliferous limestone of possible Permian age, described in the UMOS database as a coquina. It is a small nonproducing pit, claimed for dimension stone. There are no production records.

### Exploration and Mining Activity

The extent of mining activity is unknown. Minor surface disturbances can be seen on satellite imagery (Esri, base imagery) at each of the three sites within the study area. Imagery for Sage Creek shows abundant white sediment covering a little more than an acre. There does not appear to be any recent activity. Little Creek and Randolf Limestone Pits may be the same site or very close together (about 100 m apart): each scar is about 0.2 acres.

### Potential for Occurrence and Economic Analysis

Occurrences of dolomite in the study area have not proven to be productive. Dolomite (and related limestone) is commonly marketed as a salable mineral in the form of crushed stone. Much less common are the pure dolomites needed for specialty uses, such as pharmaceuticals, which would be ranked as a locatable mineral.

# Strategic and Critical Materials

No strategic or critical mineral materials are known to occur in the study area.

# Salable Minerals

Salable minerals include common varieties of sand, gravel, decorative stone, dimension stone, pumice, clay, and rock. These mineral materials are typically used in construction, agriculture, decorative building, and landscaping applications. Salable minerals are managed according to the Material Sales Act of 1947 and all other relevant State and Federal laws. The BLM's Mineral Materials Program manages the exploration, development, and disposal of salable minerals either by sales contracts or free use permit. Recreational collecting of small quantities of these materials is allowed (generally about one cubic yard), whereas larger volumes require a mineral materials sale. Salable mineral permit applications, as well as internal BLM proposals to establish free-use collection areas, are reviewed on a case-by-case basis (Bureau of Land Management, 2012).

Properties that produce salable minerals within 25 km of the Southwestern and South-Central Wyoming and Bear River Watershed study areas are listed in appendix 5. Only sand and gravel mining is currently authorized or pending in the study area, and only in the Bear River Plateau (fig. 2) part of the Bear River Watershed study area. Closed sand and gravel and stone quarries—riprap, specialty stone, and weathered granite (also known as grus)—are present in all subdivisions of the study area except the Continental Divide block).

## Sand and Gravel

Both the Southwestern and South-Central Wyoming and Bear River Watershed study area contain rock types that host naturally occurring sand and gravel, a form of construction aggregate. Sand and gravel deposits, that is, deposits that can be mined without blasting or crushing, are commonly found in

**Table 10.** Active Bureau of Land Management mineral material authorizations in the proposed withdrawal area within the (*A*) Southwestern and South-Central Wyoming study area, Wyoming, and (*B*) Bear River Watershed study area, Wyoming and Utah.

[Source: Bureau of Land Management LR2000 database, March 6, 2016. The number of cases is for the complete section that includes a proposed withdrawal area. ND, no data]

***A.*** Southwestern and South-Central Wyoming study area, Wyoming.

| Commodity | Number of approved sites | Number of pending sites |
|---|---|---|
| ND | ND | ND |

***B.*** Bear River Watershed study area, Wyoming and Utah.

| Commodity | Number of approved sites | Number of pending sites |
|---|---|---|
| Sand and gravel | 2 | 0 |
| Sand and gravel, sand | 0 | 1 |
| Sand and gravel, shale | 1 | 0 |

unconsolidated or loosely consolidated Quaternary deposits. Other, more lithified units can be quarried and crushed to produce aggregate or crushed stone. If the rock is crushed finely enough, it may also be used as sand and gravel.

The March 6, 2016, BLM LR2000 database shows three approved sites for sand and gravel, all in the Bear River Plateau area (table 10). Two of these sites are for sand and gravel, and the other site is for shale (which indicates that this is not an unconsolidated deposit). In addition, there is one pending site for sand. The sand and shale sites are on the east side of the Bear River Valley.

Following examination of imagery available in Google Earth, we conclude that the expired gravel permit, as well as one of the authorizations for sand and gravel, appear to be at the Birch Creek Reservoir and may have been used for construction of the dam. Another permit for sand and gravel may be for extraction of the deposit along the creek.

Within the study area, statistical data on production have not been reported to the USGS (Robert Callaghan and Elizabeth Scott Sangine, USGS National Minerals Information Center, written commun., March 7 and May 10, 2016, respectively). One commercial sand-and-gravel operation is within the study area. The U.S. Forest Service has 12 in-service sand-and-gravel pits in the study area; three of these are within the proposed withdrawal area in the Bear Lake Plateau block (Roger Kesterson, U.S. Forest Service, written commun., March 11, 2016). Because transport costs are typically the most significant expense in the production of aggregate, the source of the materials must be close to where they are needed. Sand and gravel in the study area is primarily in unconsolidated alluvial and glacial deposits, where harder rocks and minerals are selectively preserved and deleterious clay minerals are winnowed out.

# References Cited


Adcock, T.W., 2014, Annual report of the State Inspector of Mines of Wyoming, year ending December 31, 2014: Wyoming Department of Workforce Services, Office of Mines Inspector, Rock Springs, 115 p., accessed May 26, 2015, at http://wyoming workforce.org/_docs/mines/ar/2014.pdf.

Altschuler, Z.S., Berman, S., and Cuttitta, F., 1967, Rare earths in phosphorites—Geochemistry and potential recovery, *in* Geological Survey research 1967, chapter B: U.S. Geological Survey Professional Paper 575-B, p. 1–9. [Also available at http://pubs.usgs.gov/pp/0575b/report.pdf.]

Andersen, C.L., and Van Pelt, Lori, 2014, Wyoming's uranium drama—Risks, rewards, and remorse: WyoHistory.org, 12 p., accessed April 13, 2016, at http://www.wyohistory.org/encyclopedia/wyomings-uranium-drama-risks-reward-remorse.

Anderson, E.D., and Ponce, D.A., 2016, Geophysical data and methods used in mineral-resource assessments within the Sagebrush Focal Areas, section D *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir201620165089A.

Anderson, T.C., 2010, The geologic and hydrologic setting of NPR-3 (Teapot Dome) Wyoming and its EGS geothermal potential: Geothermal Resources Council Transactions, v. 34, p. 285–289.

Anonymous, 1960, Wyoming taconite project to get underway: Mining World, v. 22, no. 8, p. 27.

Antweiler, J .C., Love, J .D., Mosier, E.L., and Campbell, W.L., 1980, Oligocene gold-bearing conglomerate, southeast margin of Wind River Mountains, Wyoming: Wyoming Geological Survey 31st Annual Field Conference Guidebook, p. 223–228.

Austin, C.F., Austin, R.R, and Erskine, M.C., 2006. Renaissance—A geothermal resource in northern Utah: Geothermal Resources Council Transactions, v. 30, p. 853–857.

Bagley, Will, 2011, South Pass gold rush: WyoHistory.org, 7 p., accessed April 13, 2016, at http://www.wyohistory.org/encyclopedia/south-pass-gold-rush.

Banner, R.E., 1992, Physiographic provinces and surface geology of Utah: Rangelands, v. 14, no. 2, p. 106–109, accessed March, 18, 2016, at https://journals.uair.arizona.edu/index.php/rangelands/article/viewFile/11074/10347.

Barton, M., and van Bergen, M.J., 1981, Green clinopyroxenes and associated phases in a potassium-rich lava from the Leucite Hills, Wyoming: Contributions to Mineralogy and Petrology, v. 77, p. 101–114.

Bauer, C.W., and Dunning, C.P., 1979, Uraniferous phosphate resources of the Western Phosphate Field, *in* DeVoto, R.H., and Stevens, D.N., eds., Uraniferous phosphate resources, v. 1: Golden, Colorado, Earth Sciences, Inc., p. 124–247.

Bayley, R.W., 1963, A preliminary report on the Precambrian iron deposits near Atlantic City, Wyoming: U.S. Geological Survey Bulletin 1142–C, 23 p. [Also available at https://pubs.usgs.gov/bul/1142c/report.pdf.]

Bayley, R.W., Proctor, P.D., and Condie, K.C., 1973, Geology of the South Pass area, Fremont County, Wyoming: U.S. Geological Survey Professional Paper 793, 39 p. [Also available at https://pubs.er.usgs.gov/publication/pp793.]

Berg, R.R., 1983, The geometry of the Wind River Thrust, Wyoming, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colo., Rocky Mountain Association of Geologists, p. 257–262.

Berryhill, H.L., Jr., Brown, D.M., Brown, A., and Taylor, D.A., 1950, Coal resources of Wyoming: U.S. Geological Survey Circular 81, 78 p. [Also available at http://pubs.usgs.gov/circ/1950/0081/report.pdf.]

Blackett, R.E., and Wakefield, S.I., 2004, Geothermal resources of Utah—A digital atlas of Utah's geothermal resources: Utah Geological Survey Open-File Report 431, 95 p.

Blakey, R.C., 2011, Paleogeography of Western North America: Colorado Plateau Geosystems, Inc., Western North America series DVD.

Bleiwas, D.I., 2016, Locatable mineral market-demand analysis commodity profiles, section I *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir201620165089A.

Bliss, J.D., Hayes, T.S., and Orris, G.J., 2012, Limestone—A crucial and versatile industrial mineral commodity (ver. 1.1, 2012): U.S. Geological Survey Fact Sheet 2008–3089, 4 p., http://pubs.usgs.gov/fs/2008/3089/.

Boberg, W.W., 2010, The nature and development of the Wyoming uranium province: Society of Economic Geologists Special Publication 15, v. 2, p. 653–674.

Boden, T., Krahulec, K., Tabet, D., Rupke, A., and Vanden Berg, M., 2015, Utah's extractive resource industries 2014: Utah Geological Survey Circular 120, 29 p.

Botella, T., and Gasós, P., 1989, Recovery of uranium from phosphoric acid—An overview *in* The recovery of uranium from phosphoric acid: International Atomic Energy Agency Advisory Group Meeting Report-1987, Vienna, p. 17–36, accessed August 17, 2016, at http://www-pub.iaea.org/MTCD/publications/PDF/te_0533.pdf.

Breckenridge, R.M., and Hinckley, B.S., 1978, Thermal springs of Wyoming: Wyoming Geological Survey Bulletin 60, 108 p.

Bureau of Land Management, 1972, Map of South Pass historic mining area: Washington, DC., U.S. Department of the Interior Bureau of Land Management, scale: 1:126,720.

Bureau of Land Management, 1985, Energy and mineral resource assessment, manual section 3031: Washington, D.C., U.S. Department of the Interior Bureau of Land Management, accessed March 15, 2016, at http://www.blm.gov/wo/st/en/info/regulations/Instruction_Memos_and_Bulletins/blm_manual.html.

Bureau of Land Management, 1994, Mineral reports—Preparation and review: Washington, D.C., U.S. Department of the Interior Bureau of Land Management, accessed March 15, 2016, at http://www.blm.gov/wo/st/en/info/regulations/Instruction_Memos_and_Bulletins/blm_manual.html.

Bureau of Land Management, 2005, Finding of no significant impact and decision record for the Dickie Springs placer gold exploration project: Bureau of Land Management Web site, 115 p., accessed February 20, 2016, at http://www.blm.gov/style/medialib/blm/wy/information/NEPA/rsfodocs/dickiesprings.Par.53063.File.dat/00dr_fonsi.pdf.

Bureau of Land Management, 2012, Solid mineral occurrence and development potential report for the Rock Springs Field Office Resource Management Plan and associated Environmental Impact Statement: Bureau of Land Management Web site, 133 p, accessed February 16, 2016, at https://eplanning.blm.gov/epl-front-office/projects/lup/13853/38955/45164/RSRMP-MinRpt.pdf/.

Bureau of Land Management, 2015a, Record of Decision and approved resource management plan amendments of the Great Basin region, including the greater sage-grouse sub-regions of Idaho and Southwestern Montana, Nevada and northeastern California, Oregon, and Utah: Washington, D.C., Bureau of Land Management, September 2015, accessed March 15, 2016, at http://www.blm.gov/style/medialib/blm/wo/Communications_Directorate/public_affairs/sage-grouse_planning/documents.Par.44118.File.dat/GB%20ROD.pdf.

Bureau of Land Management, 2015b, Record of Decision and approved resource management plan amendments for the Rocky Mountain region, including the greater sage-grouse sub-regions of Lewiston, North Dakota, Northwest Colorado, Wyoming, and the approved resource management plans for Billings, Buffalo, Cody, HiLine, Miles City, Pompyes Pillar National Monument, South Dakota, Worland: Washington, D.C., Bureau of Land Management, September 2015, accessed March 15, 2016, at http://www.blm.gov/style/medialib/blm/wo/Communications_Directorate/public_affairs/sage-grouse_planning/documents.Par.57493.File.dat/RM%20ROD.pdf.

Bureau of Land Management, 2016, General Land Office records: Bureau of Land Management Web site, accessed April 21, 2016, at http://www.glorecords.blm.gov/.

Carnes, J.D., 2015, Phosphate rock in Wyoming: Wyoming State Geologic Survey Report of Investigations 68, 34 p.

Cathcart, J.B., 1978, Uranium in phosphate rock: U.S. Geological Survey Professional Paper 988–A, 6 p. [Also available at http://pubs.usgs.gov/pp/0988a-b/report.pdf.]

Cathcart, J.B., 1991, Phosphate deposits of the United States—Discovery, development; economic geology and outlook for the future, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., The geology of North America—Economic geology: Boulder, Colorado, Geological Society of America, U.S., Decade of North American geology, v. P-2, p. 153–164.

Cathcart, J.B., and Gulbrandsen, R.A., 1973, Phosphate deposits, *in* Brobst, D.A., and Pratt, W.P., eds., United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 515–525. [Also available at http://pubs.usgs.gov/pp/0820/report.pdf.]

Chesner, C.A., Gehard, C.A., and Tonn, C.C., 1998, A petrographic assessment of diamond potential in lamproites from the Leucite Hills, Wyoming [abs.]: Geological Society of America Abstracts with Programs, v. 30, no. 6, p. 6.

Childers, M.O., 1974, Uranium occurrences in Upper Cretaceous and Tertiary strata of Wyoming and northern Colorado: The Mountain Geologist, v. 11, no. 4, p. 131–147.

Clifton, H.E., 1969, Beach lamination—Nature and occurrence: Marine Geology, v. 7, p. 553–559.

Coleman, R.B., and Clevenger, G.W., 1967, Extraction of vanadium from phosphorus slags at Vitro Minerals & Chemical Company, *in* Hale, L.A., ed., Anatomy of the Western Phosphate Field—A guide to the geologic occurrence, exploration methods, mining engineering, and recovery technology: Intermountain Association of Geologists, 15th Annual Field Conference, Salt Lake City, Utah, p. 241–242.

Coolbaugh, M.F., Raines, G.L., Zehner, R.E., Shevenell, L., and Williams, C.F., 2006, Prediction and discovery of new geothermal resources in the Great Basin—Multiple evidence of a large undiscovered resource base: Geothermal Resources Council Transactions, v. 30, p. 867–873.

Coutant, C.G., 1899, The history of Wyoming: Laramie, Wyoming, Chaplin, Spafford and Mathison Printers, p. 639–640.

Couture, Jean-Francois and Tanaka, William, 2005, Independent Technical Report on the Rock Creek Cu-Ag Project, Montana, U.S.A.: SRK Consulting report 3UR006.01, prepared for Revett Silver Company in 2004, updated in 2005, 71 p., accessed January 5, 2010, at http://www.revettminerals.com/revProRockCreekReports.php.

Dahlkamp, F.J., 2010, Uranium deposits of the world—USA and Latin America: Berlin-Heidelberg, Springer-Verlag, 515 p.

Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., 2016, Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, 211 p., http://dx.doi.org/10.3133/sir20165089A.

DeAngelo, Jacob, 2010, Identified moderate and high temperature geothermal systems of the Western United States including AK and HI: U.S. Geological Survey database, accessed June 24, 2016, at https://catalog.data.gov/dataset/identified-moderate-and-high-temperature-geothermal-systems-of-the-western-united-states-includ.

DeAngelo, Jacob, and Williams, C.F., 2010a, Geothermal favorability map derived from logistic regression models of the Western United States (favorabilitysurface.zip): U.S. Geological Survey database, accessed December 9, 2015, at http://certmapper.cr.usgs.gov/data/geothermal/western_us/spatial/shape/favorabilitysurface.zip.

DeAngelo, Jacob, and Williams, C.F., 2010b, Identified moderate and high temperature geothermal systems of the Western United States including AK and HI: U.S. Geological Survey database, accessed December 9, 2015, at http://certmapper.cr.usgs.gov/data/geothermal/western_us/spatial/shape/identifiedgeothermalsystems.zip.

de Quadros, A.M., 1989, Report on the diamond drill program July-August 1989 at the Carissa mine property, South Pass City, Fremont County, Wyoming: Property report for Consolidated McKinney Resources Ltd.: Vancouver, British Columbia, Canada, 76 p.

Dicken, C.L., and San Juan, Carma, 2016a, BLM Legacy Rehost System (LR2000), section F *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir20165089A.

Dicken, C.L., and San Juan, C.A., 2016b, Bureau of Land Management's Land and Mineral Legacy Rehost System (LR2000) mineral use cases for the Sagebrush Mineral Resource Assessment, Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7RX996K.

Dover, J.H., 1995, Geologic map of the Logan 30'×60' quadrangle, Cache and Rich Counties, Utah, and Lincoln and Uinta Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2210, scale 1:100,000. [Also available at http://ngmdb.usgs.gov/Prodesc/proddesc_10189.htm.]

Duffield W.A., and Sass, J.H., 2003, Geothermal energy—Clean power from the Earth's heat: U.S. Geological Survey Circular 1249, 35 p., accessed March 10, 2016, at http://pubs.usgs.gov/circ/2004/c1249/.

Duval, J.S., Carson, J.M., Holman, P.B., and Darnley, A.G., 2005, Terrestrial radioactivity and gamma-ray exposure in the United States and Canada: U.S. Geological Survey Open-File Report 2005–1413, accessed March 15, 2016, at http://pubs.usgs.gov/of/2005/1413/.

East, J.E., 2013, Coal fields of the conterminous United States—National Coal Resource Assessment updated version, U.S. Geological Survey Open-File Report 2012–1205, 1 pl., 1:5,000,000-scale. [Also available at http://pubs.usgs.gov/of/2012/1205/.]

Eckstrand, O.R., 1984, Canadian mineral deposit types—A geological synopsis: Geological Survey of Canada, Economic Geology Report 36, 86 p.

Eggler, D.H., McCallum, M.E., and Smith, C.B., 1979, Megacryst assemblages in kimberlite from northern Colorado and southern Wyoming—Petrology, geothermometry-barometry, and areal distribution: *in* Boyd, F.R., and Meyer, H.O.A., eds., Proceedings of the Second International Kimberlite Conference, v. 2, Washington, D.C., American Geophysical Union, p. 213–226.

Ellis, M.S., Gunther, G.L., Ochs, A.M. Schuenemeyer, J.H., Power, H.C., Stricker, G.D., and Blake, D., 1999, Coal Resources, Greater Green River Basin, chap. GN *in* 1999 Resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625–A, 2 CD–ROMs. [Also available at http://pubs.usgs.gov/pp/p1625a/.]

Elvidge, C.D., and Lyon, R.J.P, 1985, Estimation of vegetation contribution to the 1.65/2.22 micrometer ratio in the airborne TM imagery of the Virginia Range, Nevada: International Journal of Remote Sensing, v. 6, no. 1, p. 75–88.

Emsbo, P., McLaughlin, P.I., Breit, G.N., du Bray, E.A., and Koenig, A.E., 2015, Rare earth elements in sedimentary phosphate deposits—Solution to the global REE Crisis?: Gondwana Research, v. 27, no. 2, p. 776–785.

Energy Information Administration, 2015, Annual Energy Outlook: Department of Energy, 154 p., accessed May 17, 2015 at https://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45–74.

Fairhead, J.D., Salem, A., Cascone, L., Hammill, M., Masterton, S., and Samson, E., 2011, New developments of the magnetic tilt-depth method to improve structural mapping of sedimentary basins: Geophysical Prospecting, v. 59, p. 1072–1086.

Fan, M., and Carrapa, B., 2014, Late Cretaceous–early Eocene Laramide uplift, exhumation, and basin subsidence in Wyoming—Crustal responses to flat slab subduction: Tectonics, v. 33, p. 509–529, doi:10.1002 /2012TC003221.

Feeley, T.C., 2003, Origin and tectonic implications of across-strike geochemical variations in the Eocene Absaroka Volcanic Province, United States: The Journal of Geology, v. 111, p. 329–346.

Fernette, G.L., Bellora, J.D., Bartels, M.P., Gallegos, S.M., Jordan, J.K., Tureck, K.R., and Chapman, A.L., 2016a, USMIN mineral-resource data compiled for the USGS Sagebrush Mineral Resource Assessment (SaMiRA) project: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7J964GW.

Fernette, G.L., Horton, J.H., King, Z.R., San Juan, C.A., and Schweitzer, P.N, 2016b, Prospect- and mine-related features from U.S. Geological Survey 7.5-minute topographic quadrangle maps for the Western United States: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7JD4TWT.

Filippelli, G.M., and Delaney, M.L., 1992, Similar phosphorus fluxes in ancient phosphorite deposits and a modern phosphogenic environment: Geology, v. 20, p. 709–712.

Finn, T.M., 2002, Geothermal gradient map of the southwestern Wyoming Province, southwestern Wyoming, northwestern Colorado, and northeastern Utah, *in* USGS Southwestern Wyoming Province Assessment Team, Petroleum Systems and Geologic Assessment of Oil and Gas in Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series 69–D. [Also available at http://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_16.pdf.]

Fipke, C.E., Gurney, J.J., and Moore, R.O., 1995, Diamond exploration techniques emphasising [sic] indicator mineral geochemistry and Canadian examples: Geological Survey of Canada Bulletin 423, 86 p.

Fischer, R.P., 1962, Vanadium in the United States, exclusive of Alaska and Hawaii: U.S. Geological Survey Mineral Investigations Resource Map MR–16 and pamphlet, scale 1:3,168,000.

Fischer, R.P., 1974, Exploration guides to new uranium districts and belts: Economic Geology, v. 69, p. 362–376.

Force, E.R., and Creely, Scott, 2000, Titanium mineral resources of the Western U.S.—An update: U.S. Geological Survey Open-File Report 00–442, 37 p. [Also available at http://pubs.er.usgs.gov/publication/ofr00442.]

Force, E.R., and Rich, F.J., 1989, Geologic evolution of Trail Ridge eolian heavy-mineral sand and underlying peat, northern Florida: U.S. Geological Survey Professional Paper 1499, 16 p. [Also available at http://pubs.er.usgs.gov/publication/pp1499.]

Force, E.R., Butler, R.F., Reynolds, R.L., and Houston, R.S., 2001, Magnetic ilmenite-hematite detritus in Mesozoic-Tertiary place and sandstone-hosted uranium deposits of the Rocky Mountains: Economic Geology, v. 96, p. 1445–1453.

Foster, D.A., Mueller, Mueller, P.A., Mogk, D.W., Wooden, J.L., and Vogl, J.J., 2006, Proterozoic evolution of the western margin of the Wyoming craton—Implications for the tectonic and magmatic evolution of the northern Rocky Mountains: Canadian Journal of Earth Sciences, v. 43, p. 1601–1619.

Frost, B.R., Chamberlain, K.R., Swapp, S., Frost, C.D., and Hulsebosch, T.P., 2000, Late Archean structural and metamorphic history of the Wind River Range—Evidence for a long-lived active margin on the Archean Wyoming craton: Geological Society of America Bulletin, v. 112, no. 4, p. 564–578.

Gale, H.S., 1909, Geology of the copper deposits near Montpelier, Bear Lake County, Idaho: U.S. Geological Survey Bulletin 430–B, p. 112–121. [Also available at http://pubs.er.usgs.gov/publication/b430B.]

Gardner, A.D., and Flores, V.R., 1989, Forgotten frontier—A history of Wyoming coal mining: Boulder, Colorado, Westview Press, 243 p.

Garrett, D.E., 1996, Potash deposits, processing, properties, and Uses: London, U.K., Chapman and Hall, 734 p.

Garrity, C.P., and Soller, D.R., 2009, Database of the geologic map of North America; adapted from the map by J.C. Reed, Jr., and others (2005): U.S. Geological Survey Data Series 424. [Also available at http://pubs.usgs.gov/ds/424/.]

Geodata International, Inc., 1980, Aerial radiometric and magnetic survey, Lander National Topographic Map, Wyoming, Rocky Mountains, 1979: U.S. Department of Energy Open-File Report GJBX-62-80, 2 volumes.

Geometrics, 1978, Aerial gamma ray and magnetic survey—Rock Springs, Rawlins, and Cheyenne quadrangles, Wyoming, and the Greeley quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX-17(79), 5 volumes.

Geoscience Australia, 2014, Iron ore: Geoscience Australia, Australian Resources Review, accessed Sept. 13, 2016, at http://www.ga.gov.au/scientific-topics/minerals/mineral-resources/iron-ore.

Girard, Guillaume, and Stix, John, 2012, Future volcanism at Yellowstone caldera—Insights from geochemistry of young volcanic units and monitoring of volcanic unrest: GSA Today, v. 22, p. 4–10.

Glass, G.B., 1977, Update on the Hams Fork Coal Region: Wyoming Geological Association Guidebook, 29th Annual Field Conference, p. 689–706.

Goldberg, I., Hammerbeck, E.C.I., Labuschagne, L.S., and Rossouw, C., 1992, International strategic minerals inventory summary report—Vanadium: U.S. Geological Survey Circular 930–K, 45 p. [Also available at http://pubs.usgs.gov/circ/1992/0930k/report.pdf.

Goodknight, C.S., Ludlam, J.R., Burger, J.A., Dickson, R.E., Dayvault, R.D., Dexter, J.J., and Anderson, J.R., 1982, Uranium anomalies in Wyoming and parts of adjacent States: U.S. Department of Energy, Bendix Field Engineering Corporation, Grand Junction, Colo., GJBX-3(83), 114 p.

Grauch, R.I., Desborough, G.A., Meeker, G.P., Foster, A.L., Tysdal, R.G., Herring, J.R., Lowers, H.A., Ball, B.A., Zielinski, R.A., and Johnson, E.A., 2004, Petrogenesis and mineralogic residence of selected elements in the Meade Peak phosphatic shale member of the Permian Phosphoria Formation, southeast Idaho, *in* Hein, J.R., ed., Life cycle of the Phosphoria Formation—From deposition to the post-mining environment: New York, Elsevier Science B.V., Handbook of exploration and environmental geochemistry, no. 8, p. 189–226.

Guirguis, L.A., 1985, Recovery of uranium, vanadium, and fluorine from phosphate ores: Hydrometallurgy, v. 14, p. 395–401.

Gulbrandsen, R.A., 1966, Chemical composition of phosphorites of the Phosphoria Formation: Geochimica et Cosmochimica Acta, v. 30, no. 8, p. 769–778.

Gulbrandsen, R.A., and Krier, D.J., 1980, Large and rich phosphorus resources in the Phosphoria Formation in the Soda Springs area, southeastern Idaho: U.S. Geological Survey Bulletin 1496, 25 p. [Also available at http://pubs.usgs.gov/bul/1496/report.pdf.]

Gunther, G.L., Graeber, A.E., Drake, R.M., II, 2016a, Exploration and well status, quarter miles cells—SaMiRA: U.S. Geological Survey data release, https://dx.doi.org/10.5066/F7FB511V.

Gunther, G.L., Graeber, A.E., Drake, R.M., II, 2016b, Cumulative production per township—SaMiRA: U.S. Geological Survey data release, https://dx.doi.org/10.5066/F7B85670.

Hagemann, S.G., and Cassidy, K.F., 2000, Archean orogenic lode gold deposit, *in* Hagemann, S.G., and Brown P.E., eds., Gold in 2000: Littleton, Colo., Society of Economic Geologists, Reviews in Economic Geology, v. 13, p. 9–68.

Haggerty, S.E., 1999, A diamond trilogy—Superplumes, supercontinents, and supenovae: Science, v. 285, p. 851–860.

Hahn, G.A., and Thorson, J.P., 2005, Geology of the Lisbon Valley sandstone-hosted disseminated copper deposits, Sand Juan County, Utah, *in* Bon, R.L., Gloyn, R.W., and Park, G.M., eds., Mining districts of Utah: Utah Geological Association Publication 32, p. 511–533.

Hale, L.A., 1960, Frontier Formation—Coalville, Utah, and nearby areas of Wyoming and Colorado, *in* McGookey, D.P., and Miller D.N., Jr., eds., Overthrust belt of southwestern Wyoming and adjacent areas: Wyoming Geological Association, 15th Annual Field Conference Guidebook, p. 136–146.

Hall, R.B., 1978, World nonbauxite aluminum resources—Alunite: U.S. Geological Survey Professional Paper 1076-A, 35 p. [Also available at http://pubs.usgs.gov/pp/1076a/report.pdf.]

Hammarstrom, J.M., and Zientek, M.L., 2016, Mineral-resource assessment for locatable minerals, section H *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir20165089A.

Harris, R.E., 2004, Industrial minerals and construction materials map of Wyoming: Wyoming State Geological Survey Map Series 47, 1 sheet, scale 1:500,000.

Harris R.E., Hausel, W.D., and Meyer, J.E., 1985, Metallic and industrial minerals map of Wyoming: Geological Survey of Wyoming Map Series 14, scale 1:500,000.

Harris, R.E., and Hausel, W.D., 1984, Mineral resources of Permian and Pennsylvanian rocks, *in* Goolsby, J.E., and Morton, D.K., eds., The Permian and Pennsylvanian geology of Wyoming: Wyoming Geological Association, 35th annual field conference guidebook, p. 369–382.

Hausel, W.D., 1980, Gold districts of Wyoming: Geological Survey of Wyoming Report of Investigations 23, 71 p.

Hausel, W.D., 1991, Economic geology of the South Pass granite-greenstone belt, southern Wind River Range, Western Wyoming: Geological Survey of Wyoming Report of Investigations 44, 129 p.

Hausel, W.D., 2006, Geology and geochemistry of the Leucite Hills volcanic field: Wyoming State Geological Survey Report of Investigations 56, 71 p.

Hausel, W.D., and Love, J. D., 1991, Field guide to the geology and mineralization of the South Pass region, Wind River Range, Wyoming: Wyoming Geological Association, 42nd annual field conference guidebook, p. 180–183.

Hausel, W.D., Sutherland, W.M., and Gregory, R.W., 1995, Lamproites, diamond indicator minerals, and related anomalies in the Green River Basin, Wyoming, *in* Jones, R.W., ed., Wyoming Geological Association 1995 field conference road logs, resources of southwestern Wyoming: Wyoming Geological Association, p. 45–53.

Hayes, T.S., Cox, D.P., Piatak, N.M., and Seal, R.R., II, 2015, Sediment-hosted stratabound copper deposit model: U.S. Geological Survey Scientific Investigations Report 2010–5070–M, 147 p., http://pubs.usgs.gov/sir/2010/5070/m/.

Hayes, T.S., Landis, G.P., Whelan, J.F., Rye, R.O., and Moscati, R.J., 2012, The Spar Lake strata-bound Cu-Ag deposit formed across a mixing zone between trapped natural gas and metals-bearing brine: Economic Geology, v. 107, p. 1223–1249.

Hill, P.L., Kucks, R.P., and Ravat, D.K.A., 2009, Aeromagnetic and aeroradiometric data for the conterminous United States and Alaska from the National Uranium Resources Evaluation (NURE) Program of the U.S. Department of Energy: U.S. Geological Survey Open-File Report 2009–1129. [Also available at http://pubs.usgs.gov/of/2009/1129/.]

Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineral survey, scale 1:500,000.

Hintze, L.F., Willis, G.C., Laes, D.Y.M., Sprinkel, D.A., and Brown, K.D., 2000, Digital geologic map of Utah: Utah Geological Survey, scale 1:500,000.

Hoch, A.R., and C.D. Frost, 1993, Petrographic and geochemical characteristics of mid-Tertiary igneous rocks of the Rattlesnake Hills, central Wyoming, with comparison to the Bear Lodge intrusive suite of northeast Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Wyoming State Geological Survey Memoir 5, p. 508–529.

Houston, R.S., and Murphy, J.F., 1970, Fossil beach placers in sandstones of Late Cretaceous age in Wyoming and other Rocky Mountain States: Wyoming Geological Association 22nd annual field conference guidebook, p. 241–249.

Houston, R.S., and Murphy, J.F., 1977, Depositional environment of Upper Cretaceous black sandstones of the western interior: U.S. Geological Survey Professional Paper 994–A, 29 p. [Also available at http://pubs.er.usgs.gov/ publication/pp994A.]

Houston, R.S., and Murphy, J.R., 1962, Titaniferous black sandstone deposits of Wyoming: Wyoming State Geological Survey Bulletin 49, 120 p.

IHS Energy Group, 2016, ENERDEQ U.S. well data: IHS Energy Group, online database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112, U.S.A., accessed January 11, 2016, at http://energy.ihs.com/.

Inflation Monkey, 2012, Copper price is as expensive as it was in the 1970s—Inflation adjusted historical copper price since 1900 in Pounds Sterling and U.S. Dollars: Inflation Monkey, 4 p., accessed April 27, 2016, at http://inflationmonkey.blogspot.com/2012/05/copper-price-is-as-expensive-as-it.

Jagniecki, E.A., and Lowenstein, T.K., 2015, Evaporites of the Green River Formation, Bridger and Piceance Creek Basins—Deposition, diagenesis, paleobrine chemistry, and Eocene atmospheric $CO_2$, *in* Stratigraphy and paleolimnology of the Green River Formation, Western U.S., Springer, Dordrecht, p. 277–312.

James, H.L., 1954, Sedimentary facies of iron formation: Economic Geology, v. 49, p. 235–291.

Janse, A.J.A., and Sheahan, P.A., 1995, Catalogue of the world wide diamond and kimberlite occurrences—A selective and annotative approach, *in* Griffin, W.L., ed., Diamond exploration—Into the 21st Century: Journal of Geochemical Exploration, v. 53, p. 73–111.

Jarvis, I., Burnett, W.C., Nathan, Y., Almbaydin, F.S.M., Attia, A.K.M., Castro, L.N., Flicoteaux, R., Hilmy, M.E., Husain, V., Qutawnah, A.A., Serjani, A., and Zanin, Y.N., 1994, Phosphorite geochemistry—State-of-the-art and environmental concerns: Eclogae Geologicae Helvetiae (Journal of the Swiss Geological Society), v. 87, no. 3, p. 643–700.

Jasinski, S.M., 2016, Phosphate rock: U.S. Geological Survey Mineral Commodity Summaries—2016, p. 124–125. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs–2016-phosp.pdf.]

Jasinski, S.M., Lee, W.H., and Causey, J.D., 2004, The history of production of the Western Phosphate Field, *in* Hein, J.R., ed., Life cycle of the Phosphoria Formation—From deposition to the post-mining environment: New York, Elsevier Science B.V., Handbook of Exploration and Environmental Geochemistry, no. 8, p. 45–71.

Jewell, P.W., Silberling, N.J., and Nichols, K.M., 2000, Geochemistry of the Mississippian Delle phosphatic event, eastern Great Basin, U.S.A.: Journal of Sedimentary Research, v. 70, no. 5, p. 1222–1233.

Jones, D.S., Snoke, A.W., Premo, W.R., and Chamberlain, K.R., 2010, New models for Paleoproterozoic orogenesis in the Cheyenne belt region—Evidence from the geology and U-Pb geochronology of the Big Creek Gneiss, southeastern Wyoming: Geological Society of America Bulletin, v. 122, p. 1877–1898.

Jones, J.V., III, Karl, S.M., Labay, K.A., Shew, N.B., Granitto, Matthew, Hayes, T.S., Mauk, J.L., Schmidt, J.M., Todd, Erin, Wang, Bronwen, Werdon, M.B., and Yager, D.B., 2015, GIS-Based identification of areas with mineral resource potential for six selected deposit groups, Bureau of Land Management Central Yukon Planning Area, Alaska: U.S. Geological Survey Open-File Report 2015–1021, 61 p. [Also available at http://pubs.usgs.gov/of/2015/1021/.]

Jones, N.R., Jones, R.W., and Lucke, D.W., 2011, Coal map of Wyoming—With energy production and transportation: Wyoming State Geological Survey Map Series 93, 1 sheet, scale 1:500,000. [Also available at http://sales.wsgs.wyo.gov/coal-map-of-wyoming-with-energy-production-and-transportation/.]

Jones, R.W. and Scott, J.E., 2010, Geologic map of the Rock Springs 30’×60’ Quadrangle, Sweetwater County, Wyoming: Wyoming State Geological Survey MS-96-FD, scale 1:100,000. [Also available at https://sales.wsgs.wyo.gov/catalog/product_info.php?products_id=6102.]

Karlstrom, K., and Houston, S., 1984, The Cheyenne belt—Analysis of a Proterozoic suture in southern Wyoming: Precambrian Research, v. 25, p. 415–446.

Kauwenbergh, S.J.V., 2010, World phosphate rock reserves and resources: Muscle Shoals, Alabama, International Fertilizer Development Center (IFDC) Technical Bulletin IFDC–T-75, 48 p. [Also available at http://pdf.usaid.gov/pdf_docs/Pnadw835.PDF.]

Kivi, W.J., 1940, The stratigraphy of the Phosphoria Formation of western Wyoming, with notes on the occurrence of phosphate: Laramie, Wyoming, University of Wyoming, M.A. thesis, 59 p.

Kolodny, Y., and Luz, B., 1992, Isotope signatures in phosphate deposits—Formation and diagenetic history, *in* Clauer, N., and Chaudhuri, S., eds., Isotopic signatures and sedimentary records: Berlin/Heidelberg, Springer, Lecture Notes in Earth Sciences, v. 43, p. 69–121.

Kouloheris, A.P., 1979, Uranium recovery from phosphoric acid (a process engineering review): London, Purley Press, Ltd., The Fertilizer Society of London, 22 p.

Kuck, P.H., 1985, Vanadium, *in* Mineral facts and problems: U.S. Bureau of Mines Bulletin 675, p. 895–915.

Kuehner, S.M., 1980, Petrogenesis of ultrapotassic rocks, Leucite Hills, Wyoming: London, Ontario, University of Western Ontario M.S. thesis, 197 p.

Kuehner, S.M., Edgar, A.D., and Arima, M., 1981, Petrogenesis of ultrapotassic rocks from the Leucite Hills, Wyoming: American Mineralogist, v. 66, p. 663–677.

Lange, R.A., Carmichael, I.S.E., and Hall, C.M., 2000, $^{40}Ar/^{39}Ar$ chronology of the Leucite Hills, Wyoming—Eruption rates, erosion rates, and an evolving temperature structure of the underlying mantle: Earth and Planetary Science Letters, v. 174, p. 329–340.

Law, B.E., 1995, Southwestern Wyoming Province (037), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National Assessment of the United States of oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, release 2, CD-ROM. [Also available at http://certmapper.cr.usgs.gov/data/noga95/prov37/text/prov37.pdf.]

Layman, Susan, 2012, A history of Wyoming’s Carissa gold mine: Mining History Journal, v. 19, p. 36–49.

Lenardic, A., 1997, On the heat flow variation from Archean cratons to Proterozoic mobile belts: Journal of Geophysical Research, v. 102, B1, p. 709–721.

Lienau, P.J., and Ross, H., 1996, Final report—Low-temperature resource assessment program, Geo-Heat Center: Klamath Falls, Ore., Oregon Institute of Technology, 72 p.

Link, Paul, and DeGrey, Laura, 2016, Mesozoic thrust belt—Idaho State University Web site, accessed March 18, 2016, at http://geology.isu.edu/Digital_Geology_Idaho/Module5/mod5.htm.

Love, J.D., 1960, Cenozoic sedimentation and crustal movement in Wyoming: American Journal of Science, v. 258-A, p. 204–214.

Love, J.D., and Antweiler, J.C., 1973, Copper, silver, and zinc in the Nugget Sandstone, western Wyoming: Wyoming Geological Association 25th field conference guidebook, p. 139–147.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey (Wyoming State Geological Survey release 2014), 3 pls., scale 1:500,000. [Also available at http://ngmdb.usgs.gov/Prodesc/proddesc_16366.htm.]

Love, J.D., Antweiler, J.C., and Mosier, E.L., 1978, A new look at the origin and volume of the Dickie Springs-Oregon Gulch placer gold at the south end of the Wind River Mountains: Wyoming Geological Association 30th annual field conference guidebook, p. 379–391.

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Wyoming Geological Survey Map Series 41.

Love, J.D., Smith, L.E., Browne, D.G., and Carter, L.M., 2003, Vanadium deposits in the Lower Permian Phosphoria Formation, Afton area, Lincoln County, western Wyoming: U.S. Geological Survey Professional Paper 1637, 28 p. [Also available at http://pubs.usgs.gov/pp/1637/.]

Ludington, Steve, Moring, B.C., Miller, R.J., Stone, P.A., Bookstrom, A.A., Bedford, D.R., Evans, J.G., Haxel, G.A., Nutt, C.J., Flyn, K.S., and Hopkins, M.J., 2007, Preliminary integrated geologic map databases for the United States—Western States—California, Nevada, Arizona, Washington, Oregon, Idaho, and Utah (ver. 1.3, December 2007): U.S. Geological Survey Open-File Report 2005–1305. [Also available at http://pubs.usgs.gov/of/2005/1305/.]

M'Gonigle, J.W., and Dover, J.H., 2004, Geologic map of the Kemmerer 30'×60' quadrangle, Lincoln, Uinta, and Sweetwater Counties, Wyoming: Wyoming State Geological Survey Open-File Report 04–7, scale: 1:100,000. [Also available at http://sales.wsgs.wyo.gov/wsgs-geologic-map-of-the-kemmerer-30-x-60-quadrangle-lincoln-uinta-and-sweetwater-counties-wyoming/.]

Magoon, L. B., and Schmoker, J. W., 2000, The total petroleum system—The natural fluid network that constrains the assessment unit, chapter PS *in* U.S. Geological Survey World Energy Assessment Team, U.S. Geological Survey World Petroleum Assessment 2000—Description and results: U.S. Geological Survey Digital Data Series 60, ver. 1.0, CD-ROM, disk one, 31 p. [Also available at http://pubs.usgs.gov/dds/dds-060/.]

Magyar, M.J., 2003, Vanadium: U.S. Geological Survey Minerals Yearbook 2003, p. 80.1–80.8. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/vanadium/vanadmyb03.pdf.]

Mansfield, G.R., 1940, Phosphate deposits of the United States: Economic Geology, v. 35, p. 405–429.

Maughan, E.K., 1994, Phosphoria Formation (Permian) and its resource significance in the western interior, USA, *in* Embry, A.F., Beauchamp, B., and Glass, D.J., eds., Pangea—Global environments and resources: Canadian Society of Petroleum Geologists Memoir 17, p. 479–495.

McDowell, F.W., 1971, K-Ar ages of igneous rocks from the Western United States: Isochron/West, no. 2, p. 1–16.

McGowan, K.I., 1990, Thermochemical conditions for the formation of Archean lode gold mineralization at Atlantic City-South Pass, Wyoming: Ames, Iowa, Iowa State University, Ph.D. dissertation, 159 p.

McKelvey, V.E., Smith, L.E., Hoppin, R.A., and Armstrong, F.C., 1953, Stratigraphic sections of the Phosphoria Formation in Wyoming, 1947–48: U.S. Geologic Survey Circular 210, 35 p., [Also available at http://pubs.usgs.gov/circ/1953/0210/report.pdf.]

McKelvey, V.E., Williams, J.S., Sheldon, R.P., Cressman, E.R., Cheney, T.M., and Swanson, R.W., 1959, The Phosphoria, Park City, and Shedhorn Formations in the Western Phosphate Field: U.S. Geological Survey Professional Paper 313–A, 47 p. [Also available at http://pubs.usgs.gov/pp/0313a/report.pdf.]

Mine Safety and Health Administration, 2016, Mine Data Retrieval System: U.S. Department of Labor Web site, accessed March 31, 2016, at http://arlweb.msha.gov/drs/drshome.htm.

Morgan, T.L., George, W.E., Gallimore, D.L., Hansel, J.M., Jackson, C.K., and Bunker, M.E., 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Rock Springs NTMS quadrangle, Wyoming, including concentrations of forty-two additional elements: Grand Junction, Colo., U.S. Department of Energy, Los Alamos Scientific Laboratory informal report LA-7543-MS, GJBX-126(81), 172 p.

Moyle, R.W., 1981, Surface geology, *in* Greer, D.C., Gurgel, K.D., Wahlquist, W.L., Christy, H.A., and Peterson, G.B., Atlas of Utah: Provo, Utah, Weber State College and Brigham Young University Press, 300 p.

Mueller, P.A., and Frost, C.D., 2006, The Wyoming Province—A distinctive Archean craton in Laurentian North America: Canadian Journal of Earth Sciences, v. 43, p. 1391–1397.

Muffler, L.P.J., 1979, Assessment of geothermal resources of the United States—1978: U.S. Geological Survey Circular 790, 163 p. [Also available at http://pubs.usgs.gov/circ/1979/0790/report.pdf.]

Nichols, K.M., and Silberling, N.J., 1991a, Petrology and depositional setting of Mississippian rocks associated with an anoxic event at Samak, western Uinta Mountains, Utah: U.S. Geological Survey Bulletin 1787–S, p. S1–S13. [Also available at http://pubs.usgs.gov/bul/1787s-t/report.pdf.]

Nichols, K.M., and Silberling, N.J., 1991b, Petrology and significance of a Mississippian (Osagean-Meramecian) anoxic event, Lakeside Mountains, northwestern Utah: U.S. Geological Survey Bulletin 1787–T, p. T1–T12. [Also available at http://pubs.usgs.gov/bul/1787s-t/report.pdf.]

Orris, G.J., 2011, Deposit model for closed-basin potash-bearing brines: U.S. Geological Survey Open-File Report 2011–1283, 11 p. [Also available at http://pubs.usgs.gov/of/2011/1283/.]

Orris, G.J., Cocker, M.D., Dunlap, P., Wynn, Jeff, Spanski, G.T., Briggs, D.A., and Gass, L., with contributions from Bliss, J.D., Bolm, K.S., Yang, C., Lipin, B.R., Ludington, S., Miller, R.J., and Slowakiewicz, M., 2014, Potash—A global overview of evaporite-related potash resources, including spatial databases of deposits, occurrences, and permissive tracts: U.S. Geological Survey Scientific Investigations Report 2010–5090–S, 76 p., and spatial data, http://dx.doi.org/10.3133/sir20105090S.

Osterwald, F.W., Osterwald, D.B., Long, Jr., J.S., Wilson, W.H., 1966, Mineral resources of Wyoming: Geological Survey of Wyoming Bulletin 50, 287 p.

Parks, H.L., Zientek, M.L., Jenkins, M.C., Hennings, C.K., Wallis, J.C., Nguyen, D.M., and Cossette, P.M., 2016, Previous mineral-resource assessment data compilation for the U.S. Geological Survey Sagebrush Mineral-Resource Assessment project: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7736P0C.

Patterson, C.G., Kulik, D.M., Loen, J.S., Koesterer, M.E., and Scott, D.C., 1987, Mineral resources of the Honeycomb Buttes Wilderness Study Area, Fremont and Sweetwater Counties, Wyoming: U.S. Geological Survey Bulletin 1757–B, p. B1–B19. [Also available at http://pubs.er.usgs.gov/ publication/b1757B.]

Peters, S.E., and Gaines, 2012, Formation of the Great Unconformity as a trigger for the Cambrian explosion: Nature, v. 484, p. 363–366.

Piper, D.Z., 2001, Marine chemistry of the Permian Phosphoria Formation and basin, southeast Idaho: Economic Geology, v. 96, p. 599–620.

Piper, D.Z., and Link, P.K., 2002, An upwelling model for the Phosphoria sea—A Permian, ocean-margin sea in the northwest United States: American Association of Petroleum Geologists Bulletin, v. 86, no. 7, p. 1217–1235.

Powers, R.B., 1983, Petroleum potential of wilderness lands in Wyoming-Utah-Idaho thrust belt; petroleum potential of wilderness lands in the Western United States: U. S. Geological Survey Circular 902–N, 14 p. [Also available at http://pubs.usgs.gov/circ/1983/0902n/report.pdf.]

Rabchevsky, G.A., 1995, Phosphate rock: U.S. Geological Survey Minerals Information, p. 1–7. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/540495.pdf.

Ragheb, M., and Khasawneh, M., 2010, Uranium fuel as byproduct of phosphate fertilizer production: 1st International Nuclear and Renewable Energy Conference (INREC10), Amman, Jordan, p. 1–15.

Reed, M.J., ed., 1983, Assessment of low-temperature geothermal resources of the United States—1982: U.S. Geological Survey Circular 892, 73 p. [Also available at https://pubs.er.usgs.gov/publication/cir892.]

Reed, M.J., Mariner, R.H., Brook, C.A., and Sorey, M.L., 1983, Selected data for low-temperature (less than 90°C) geothermal systems in the United States, reference data for U.S. Geological Survey Circular 892: U.S. Geological Survey Open-file Report 83–250, 132 p. [Also available at http://pubs.usgs.gov/of/1983/0250/report.pdf.]

Reheis, M.C., Laabs, B.J.C., and Kaufman, D.S., 2009, Geology and geomorphology of Bear Lake Valley and upper Bear River, Utah and Idaho, *in* Rosenbaum, J.G., and Kaufman, D.S., eds., Paleoenvironments of Bear Lake, Utah and Idaho, and its catchment: Geological Society of America Special Paper 450, p. 15–48. [Also available at http://dx.doi.org: 10.1130/2009.2450(02).]

Roberts, Sheila, 1989, Wyoming geomaps: Geological Survey of Wyoming Educational Series 1, 42 p., http://wsgs.wyo.gov/products/wsgs-1989-es-1.pdf.

Roberts, S.B., 2005, Geologic assessment of undiscovered petroleum resources in the Wasatch-Green River composite total petroleum system, southwestern Wyoming province, Wyoming, Colorado, and Utah, *in* USGS Uinta-Piceance Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series 69–D, 26 p. [Also available at http://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_12.pdf.]

Rockwell, B.W., 2013, Automated mapping of mineral groups and green vegetation from Landsat Thematic Mapper imagery with an example from the San Juan Mountains, Colorado: U.S. Geological Survey Scientific Investigations Map 3252, 25 p. pamphlet, 1 map sheet, scale 1:325,000. [Also available at http://pubs.usgs.gov/sim/3252/.]

Rockwell, B.W., 2016, Remote sensing, section E *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir20165089A.

Rockwell, B.W., Bonham, L.C., and Giles, S.A., 2015, USGS national map of surficial mineralogy: U.S. Geological Survey Web site, accessed May 31, 2016, at http://cmerwebmap.cr.usgs.gov/usminmap.html.

Roehler, H.W., 1989, Origin and distribution of six heavy-mineral placer deposits in the coastal-marine sandstones in the Upper Cretaceous McCourt Sandstone Tongue of the Rock Springs Formation, southwest Wyoming: U.S. Geological Survey Bulletin 1867, 34 p. [Also available at http://pubs.usgs.gov/bul/1867/report.pdf.]

Roehler, H.W., 1990, West-east stratigraphic correlations of surface and subsurface sections of the intertongued Wasatch and Green River Formations, northern Green River Basin, Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2149. [Also available at http://pubs.usgs.gov/mf/2149/plate-1.pdf.]

Roehler, H.W., 1991, Revised stratigraphic nomenclature for the Wasatch and Green River Formations of Eocene age, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–B, p. B1–B38. [Also available at http://pubs.usgs.gov/pp/1506b/report.pdf.]

Roehler, H.W., 1992, Introduction to greater Green River Basin geology, physiography, and history of investigations, *in* Geology of the Eocene Wasatch, Green River, and Bridger (Washakie) Formations, greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–A, 13 p. [Also available at http://pubs.usgs.gov/pp/1506a/report.pdf.]

Rogers, M.C., 1995, Phosphorite characteristics, *in* Rogers, M.C., Thurston, P.C., Fyon, J.A., Kelly, R.I., and Breaks, F.W., eds., Descriptive mineral deposit models of metallic and industrial deposit types and related mineral potential assessment criteria: Ontario Geological Survey Open-File Report 5916, p. 155–158.

Rubin, Bruce, 1970, Uranium roll zonation in the southern Powder River basin, Wyoming: Earth Science Bulletin (Wyoming Geological Association), v. 3, no. 4, p. 5–12.

Rubey, W.W., 1973, New Cretaceous formations in the western Wyoming thrust belt: U.S. Geological Survey Bulletin 1372-I, p. I1–I35. [Also available at http://pubs.usgs.gov/bul/1372i/report.pdf.]

Rubey, W.W., Oriel, S.S., and Tracey, J.I., 1980, Geologic map and structure sections of the Cokeville 30-minute quadrangle, Lincoln and Sublette Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–1129, scale 1:62,500. [Also available at https://pubs.er.usgs.gov/publication/i1129.]

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1975, Geology of the Sage and Kemmerer 15-minute quadrangles, Lincoln County, Wyoming: U.S. Geological Survey Professional Paper 855, 18 p. [Also available at https://pubs.er.usgs.gov/publication/pp855.]

Ruttenberg, K.C., 2005, The global phosphorus cycle, *in* Schlesinger, W.H., ed., Biogeochemistry, Treatise on Geochemistry: Oxford, Elsevier, v. 8, p. 585–643.

Ryder, R.T., 1988, Greater Green River Basin, *in* Sloss, L.L., ed., Sedimentary cover—North American craton: The Geological Society of America, Decade of North American Geology, p. 154–165.

Ryer, T.A., McClurg, J.J., and Muller, M.M., 1987, Dakota-Bear River paleoenvironments, depositional history and shoreline trends—Implications for foreland basin paleotectonics, southwestern Green River Basin and southern Wyoming overthrust belt *in* Wyoming Geological Association 38th field conference guidebook, p. 179–206.

San Juan, C.A., Horton, J.D., Parks, H.L., Mihalasky, M.J., Anderson, E.D., Benson, M.E., Box, S.E., Cossette, P.M., Denning, P.D., Giles, S.A., Hall, S.M., Hayes, T.S., Hearn, B.C., Jr., Hofstra, A.H., John, D.A., Ludington, S., Lund, K., Mauk, J.L., Robinson, G.R., Jr., Rockwell, B.W., Rytuba, J.J., Smith, S.M., Stillings, L.L., Van Gosen, B.S., Vikre, P.G., Wallis, J.C., Wilson, A.B., Zientek, M.L., and Zürcher, L., 2016, Locatable mineral assessment tracts for the U.S. Geological Survey Sagebrush Mineral-Resource Assessment Project: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7833Q4R.

Schulz, A.R., and Cross, Whitman, 1912, Potash-bearing rocks of the Leucite Hills, Sweetwater County, Wyoming: U.S. Geological Survey Bulletin 512, 39 p. [Also available at https://pubs.er.usgs.gov/publication/b512.]

Scott-Smith, B.H., 1996, Lamproites, chapter 12, *in* Mitchell, R.H., ed., Undersaturated alkaline rocks—Mineralogy, petrology, and economic potential: Nepean, Ontario, Canada, Mineralogical Association of Canada Short Course v. 24, p. 259–270.

Scott, G.R., 1975, Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoirs, v. 144, p. 227–248.

Shannon, S.S., Jr., Sandoval, W.F., Montoya, J.D., Miner, M.M., Simi, O.R., Talcott, C.L., and Pirtle, D.J., 1979, Uranium hydrogeochemical and stream sediment reconnaissance of the Lander NTMS quadrangle, Wyoming, including concentrations of forty-three additional elements: Grand Junction, Colo., U.S. Department of Energy, Los Alamos Scientific Laboratory informal report LA-7512-MS, GJBX-1(83), 402 p.

Sheldon, R.P., 1957, Physical stratigraphy of the Phosphoria Formation in northwestern Wyoming, Contributions to economic geology: U.S. Geological Survey Bulletin 1042–E, p. 105–185. [Also available at http://pubs.usgs.gov/bul/1042e/report.pdf.]

Sheldon, R.P., Cressman, E.R., Carson, L.D., and Smart, R.A., 1954, Stratigraphic sections of the Phosphoria Formation in Wyoming, 1952: U.S. Geological Survey Circular 325, 24 p. [Also available at https://pubs.er.usgs.gov/publication/cir325.]

Sherborne, J.D., Jr., Pavlak, S.J., Peterson, C.H., and Buckovic, W.A., 1980, Uranium deposits of the Sweetwater mine area, Great Divide Basin, Wyoming, *in* Third annual uranium seminar, Casper, Wyoming, September 9–12, 1979: New York, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 27–37.

Skinner, B.J., and Barton, P.B., Jr., 1973, Genesis of mineral deposits: Annual Review of Earth and Planetary Sciences, v. 1, p. 183–211.

Smedes, H.W., and Prostka, H. J., 1972, Stratigraphic framework of the Absaroka Volcanic Supergroup in the Yellowstone National Park region: U.S. Geological Survey Professional Paper 729–C, p. 1–33. [Also available at https://pubs.er.usgs.gov/publication/pp729C.]

Smith, S.M., 1997, National Geochemical Database—Reformatted data from the National Uranium Resource Evaluation (NURE) Hydrogeochchemical and Stream Sediment Reconnaissance (HSSR) Program: U.S. Geological Survey Open-File Report 97–492, accessed, June 20, 2016, at https://pubs.er.usgs.gov/publication/ofr97492.

Smith, S.M., Kelley, K.D., Folger, H.W., Yager, D.B., Granitto, Matthew, and Giles, S.A., 2016, Geochemical data, section C *of* Day, W.C., Hammarstrom, J.M., Zientek, M.L., and Frost, T.P., eds., Overview with methods and procedures of the U.S. Geological Survey mineral resource assessment of the Sagebrush Focal Areas of Idaho, Montana, Nevada, Oregon, Utah, and Wyoming: U.S. Geological Survey Scientific Investigations Report 2016–5089–A, http://dx.doi.org/10.3133/sir20165089A.

Snoke, A.W., 1993, Geologic history of Wyoming within the tectonic frame work of the North American Cordillera, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming, Memoirs, no. 5, p. 3–56.

Stephens, J.G., 1964, Geology and uranium deposits at Crooks Gap, Fremont County, Wyoming, with a section on gravity and seismic studies: U.S. Geological Survey Bulletin 1147, 82 p., 10 pls. [Also available at https://pubs.er.usgs.gov/publication/b1147F.]

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2007, Preliminary integrated geologic map databases for the United States–Central States–Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana (ver. 1.2, December 2007): U.S. Geological Survey Open-File Report 2005–1351. [Also available at http://pubs.usgs.gov/of/2005/1351/.]

Sullivan, Raymond, 1980, A stratigraphic evaluation of the Eocene rocks of southwestern Wyoming: Geological Survey of Wyoming Report of Investigation No. 20, 50 p.

Sutherland, W.M. and Luhr, S.C., 2011, Preliminary bedrock geologic map of the Farson 30’×60’ Quadrangle, Sweetwater, Sublette and Fremont Counties, Wyoming: Wyoming State Geological Survey Open-File Report 11-6, scale 1:100,000. [Also available at https://sales.wsgs.wyo.gov/catalog/product_info.php?products_id=5895.]

Sutherland, W.M., and Hausel, W.D., 2006, Geologic map of the South Pass 30’×60’ Quadrangle, Fremont and Sweetwater Counties, Wyoming: Wyoming State Geological Survey MS-70-FD, scale 1:100,000. [Also available at https://sales.wsgs.wyo.gov/catalog/product_info.php?products_id=5947.]

Tooker, E.W., 1992, Industrial minerals in the Basin and Range region—Workshop proceedings: U.S. Geological Survey Bulletin 2013, 132 p. [Also available at http://pubs.usgs.gov/bul/2013/report.pdf.]

Tuck, C.A., 2016, Iron ore: U.S. Geological Survey Mineral Commodity Summaries 2016, p. 90–91, accessed Sept. 13, 2016, at http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/mcs-2016-feore.pdf.

U.S. Geological Survey, 2004, Assessment of undiscovered oil and gas resources of the Wyoming Thrust Belt Province, 2003: U.S. Geological Survey Fact Sheet 2004–3025. [Also available at http://pubs.usgs.gov/fs/2004/3025/fs-2004-3025.pdf.]

U.S. Geological Survey, 2008, The mineral industry of Wyoming, *in* Area reports—Domestic: U.S. Geological Survey Minerals Yearbook 2005, v. II, p. 53.1–53.6, accessed June 15, 2015 at http://minerals.usgs.gov/minerals/pubs/state/2005/myb2-2005-wy.pdf.

U.S. Geological Survey, 2010, The mineral industry of Wyoming [advance release], *in* Area reports—Domestic: U.S. Geological Survey Minerals Yearbook 2007, v. II, p. 53.1–53.8, accessed June 15, 2015, at http://minerals.usgs.gov/minerals/pubs/state/2007/myb2-2007-wy.pdf.

U.S. Geological Survey, 2012, The mineral industry of Wyoming, *in* Area reports—Domestic: U.S. Geological Survey Minerals Yearbook 2008, v. II, p. 53.1–53.6, accessed June 15, 2015, at http://minerals.usgs.gov/minerals/pubs/state/2008/myb2-2008-wy.pdf.

U.S. Geological Survey, 2014, Physiographic divisions of the conterminous U.S., *from* Fenneman, N.M., and Johnson, D.W., 1946, Physical Divisions of the United States: U.S. Geological Survey Special Map, 1:7,000,000 scale [digital data], accessed June 24, 2016, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml.

U.S. Geological Survey, 2016, Mineral Resource Data System: U.S. Geological Survey Web site, accessed March 15, 2016, at http://mrdata.usgs.gov/mrds/.

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2002, Assessment of undiscovered oil and gas resources of the Southwestern Wyoming Province, 2002: U.S. Geological Survey Fact Sheet 145–02, 2 p. [Also available at http://pubs.usgs.gov/fs/fs-145-02/.]

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005a, Petroleum Systems and Geologic Assessment of Oil and Gas in the Southwestern Wyoming Province, Wyoming, Colorado and Utah: U.S. Geological Survey Digital Data Series 69–D. [Also available at http://pubs.usgs.gov/dds/dds-069/dds-069-d/.]

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005b, The Southwestern Wyoming Province—Introduction to a geologic assessment of undiscovered oil and gas resources, chap. 2 *of* Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series 69–D, 34 p. [Also available at http://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_2.pdf.]

Ulrich, A.E., Schnug, E., Prasser, H.-M., and Frossard, E., 2014, Uranium endowments in phosphate rock: Science of the Total Environment, v. 478, p. 226–234.

Utah Division of Oil, Gas, and Mining, 2016, Utah minerals program permit database: Utah Division of Oil, Gas, and Mining Database, accessed January 11, 2016, at http://linux3.ogm.utah.gov/WebStuff/wwwroot/minerals/mineralstaskinfo.php.

Utah Geological Survey, 2015, Utah Mineral Occurrence System database: Utah Geological Survey Web site, accessed December 11, 2015, at http://geology.utah.gov/resources/data-databases/utah-mineral-occurrence-system/.

Van Gosen, B.S., Fey, D.L., Shah, A.K., Verplanck, P.l., and Hoefen, T.M., 2014, Deposit model for heavy-minerals sands in coastal environments: U.S. Geological Survey Scientific Investigations Report 2010–5070–L, 51 p., https://pubs.er.usgs.gov/publication/sir20105070L.

Westmoreland Coal Company, 2016, Kemmerer Mine—Wyoming: Westmoreland Coal Company Web page, accessed September 22, 2016, at http://westmoreland.com/location/kemmerer-mine-wyoming/.

Williams, C.F., and DeAngelo, J., 2008, Mapping geothermal potential in the Western United States: Geothermal Resources Council Transactions, v. 32, p. 181–187.

Williams, C.F., and DeAngelo, J., 2011, Evaluation of approaches and associated uncertainties in the estimation of temperatures in the upper crust of the Western United States: Geothermal Resources Council Transactions, v. 35, p. 1599–1606.

Williams, C.F., Reed, M.J, DeAngelo, J., and Galanis, S.P., Jr., 2009, Quantifying the undiscovered geothermal resources of the United States: Geothermal Resources Council Transactions, v. 33, p. 995–1003.

Williams, C.F., Reed, M.J., Mariner, R.H., DeAngelo, J., and Galanis, S.P., Jr., 2008, Assessment of moderate- and high-temperature geothermal resources of the United States: U.S. Geological Survey Fact Sheet 2008–3082, 4 p. [Also available at http://pubs.usgs.gov/fs/2008/3082/.]

Wilson, A.B., 2015, Uranium in the Wyoming Landscape Conservation Initiative Study Area, southwestern Wyoming: U.S. Geological Survey Open-File Report 2014–1123, 33 p., 1 pl. [Also available at http://dx.doi.org/10.3133/ofr20141123.]

Winterhalder, E.C., 1954, Preliminary reconnaissance for uranium in the Green River Basin and the Rock Springs Uplift, Sweetwater and Fremont Counties, Wyoming: U.S Atomic Energy Commission RME-1045, 10 p.

Wood, G.H., Jr., Kehn, T.M., Carter, M.D., and Culbertson, W.C., 1983, Coal resource classification system of the U.S. Geological Survey: U.S. Geological Survey Circular 891, 65 p. [Also available at http://pubs.usgs.gov/circ/1983/0891/report.pdf.]

Wyoming Department of Environmental Quality, 2015, Wyoming coal mine permit boundaries spatial data: Wyoming Department of Environmental Quality unpublished database.

Wyoming Department of Environmental Quality, 2015, A viewer of land quality active permits: Wyoming Department of Environmental Quality Online Viewer and Database, accessed December 23, 2015, at https://gis.deq.wyoming.gov/maps/lqd_permit_public/index.html.

Wyoming Department of Revenue, 1973–1978, Annual reports: Cheyenne, Wyoming Department of Revenue.

Wyoming State Board of Equalization, 1948–1972, *in* Wyoming State Board of Equalization, 1926–1972, Biennial reports: Cheyenne, Wyoming State Board of Equalization.

Wyoming State Geological Survey, 2011, Principal coal-bearing and related stratigraphic units in Wyoming: Wyoming State Geological Survey, accessed June 10, 2016, at http://www.wsgs.wyo.gov/docs/wsgs-web-coal-strat.pdf.

Wyoming State Geological Survey, 2016, Oil and gas areal fields 2012: Wyoming State Geological Survey vector digital data, accessed June 24, 2016, at http://www.wsgs.wyo.gov/pubs-maps/gis.

Yeend, W.E., 1986, Descriptive model of placer Au-PGE, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 261–263.

Yonkee, W.A., and Weil, A.B., 2011, Evolution of the Wyoming salient of the Sevier fold-thrust belt, Northern Utah to Western Wyoming, *in* Sprinkel, D.A., Yonkee, W.A., and Chidsey, T.C., Jr., eds., Sevier thrust belt—Northern and central Utah and adjacent areas: Utah Geological Association Publication, v. 40, 56 p.

Zeller, H.D., and Stephens, E.V., 1969, Geology of the Oregon Buttes area, Sweetwater, Sublette, and Fremont Counties, southwestern Wyoming: U.S. Geological Survey Bulletin 1256, 60 p. [Also available at https://pubs.usgs.gov/bul/1256/report.pdf.]

Zhang, P., Wiegel, R., and El-Shall, H., 2006, Phosphate rock, *in* Kogel, J.E., Trivedi, N.C., Barker, J.M., and Krukowski, S.T., eds., Industrial minerals and rocks—Commodities, markets, and uses: Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, Inc., p. 703–722.

Zientek, J.L., Bliss, J.D., Broughton, D.W., Christie, Michael, Denning, P.D., Hayes, T.S., Hitzman, M.W., Horton, J.D., Frost-Killian, Susan, Jack D.J., Master, Sharad, Parks, H.L., Taylor, C.D., Wilson, A.B., Wintzer, N.E., and Woodhead, Jon, 2014, Sediment-hosted stratabound copper assessment of the Neoproterozoic Roan Group, Central African Copperbelt, Katanga Basin, Democratic Republic of Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–T, 162 p., http://pubs.usgs.gov/sir/2010/5090/t/index.html.

Zientek, M.L., Hayes, T.S., and Hammarstrom, J.M., 2013a, Overview of a new descriptive model for sediment-hosted stratabound copper deposits, chap. 1 *of* Taylor C.D., Causey, J.C., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., and Zientek, M.L., Descriptive models, grade-tonnage relations and databases for the assessment of sediment-hosted copper deposit—With emphasis on deposits in the Central African Copperbelt, Democratic Republic of the Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–J, p. 2–15, http://pubs.usgs.gov/sir/2010/5090/j/index.html.

Zientek, M.L., Hayes, T.S., and Taylor, C.D., 2013b, Grade and tonnage relations for sediment-hosted stratabound copper deposits, chap. 2 *of* Taylor C.D., Causey, J.C., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., and Zientek, M.L., Descriptive models, grade-tonnage relations and databases for the assessment of sediment-hosted copper deposit—With emphasis on deposits in the Central African Copperbelt, Democratic Republic of the Congo and Zambia: U.S. Geological Survey Scientific Investigations Report 2010–5090–J, p. 17–59, http://pubs.usgs.gov/sir/2010/5090/j/index.html.

# Appendixes

# Appendix 1. Mineral Potential Classification System

The approach to classification of the qualitative mineral-resource potential for locatable minerals followed that prescribed in Bureau of Land Management (BLM) Manual Sections 3031 and 3060 defined originally by Goudarzi (1984) (fig. 1–1).

## Level of Potential

N. The geologic environment, the inferred geologic processes, and the lack of mineral occurrences do not indicate potential for accumulation of mineral resources.

L. The geologic environment and the inferred geologic processes indicate low potential for accumulation of mineral resources.

M. The geologic environment, the inferred geologic processes, and the reported mineral occurrences or valid geochemical/geophysical anomaly indicate moderate potential for accumulation of mineral resources.

H. The geologic environment, the inferred geologic processes, the reported mineral occurrences and (or) valid geochemical/geophysical anomaly, and the known mines or deposits indicate high potential for accumulation of mineral resources. The “known mines and deposits” do not have to be within the area that is being classified, but have to be within the same type of geologic environment.

ND. Minerals potential not determined due to lack of useful data. This does not require a level of certainty qualifier.

## Level of Certainty

A. The available data are insufficient and (or) cannot be considered as direct or indirect evidence to support or refute the possible existence of mineral resources within the respective area.

B. The available data provide indirect evidence to support or refute the possible existence of mineral resources.

C. The available data provide direct but quantitatively minimal evidence to support or refute the possible existence of mineral resources.

D. The available data provide abundant direct and indirect evidence to support or refute the possible existence of mineral resources.

For the determination of “no potential” use N/D. This class shall be seldom used, and when used it should be for a specific commodity only. For example, if the available data show that the surface and subsurface types of rock in the respective area are batholithic (igneous intrusive), one can conclude, with reasonable certainty, that the area does not have potential for coal.

As used in this classification, potential refers to potential for the presence (occurrence) of a concentration of one or more energy and (or) mineral resources. It does not refer to or imply potential for development and (or) extraction of the mineral resource(s). It does not imply that the potential concentration is or may be economic, that is, could be extracted profitably.

## Reference Cited

Goudarzi, G.H., compiler, 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84–787, 41 p., accessed December 9, 2015, at https://pubs.er.usgs.gov/publication/ofr84787.

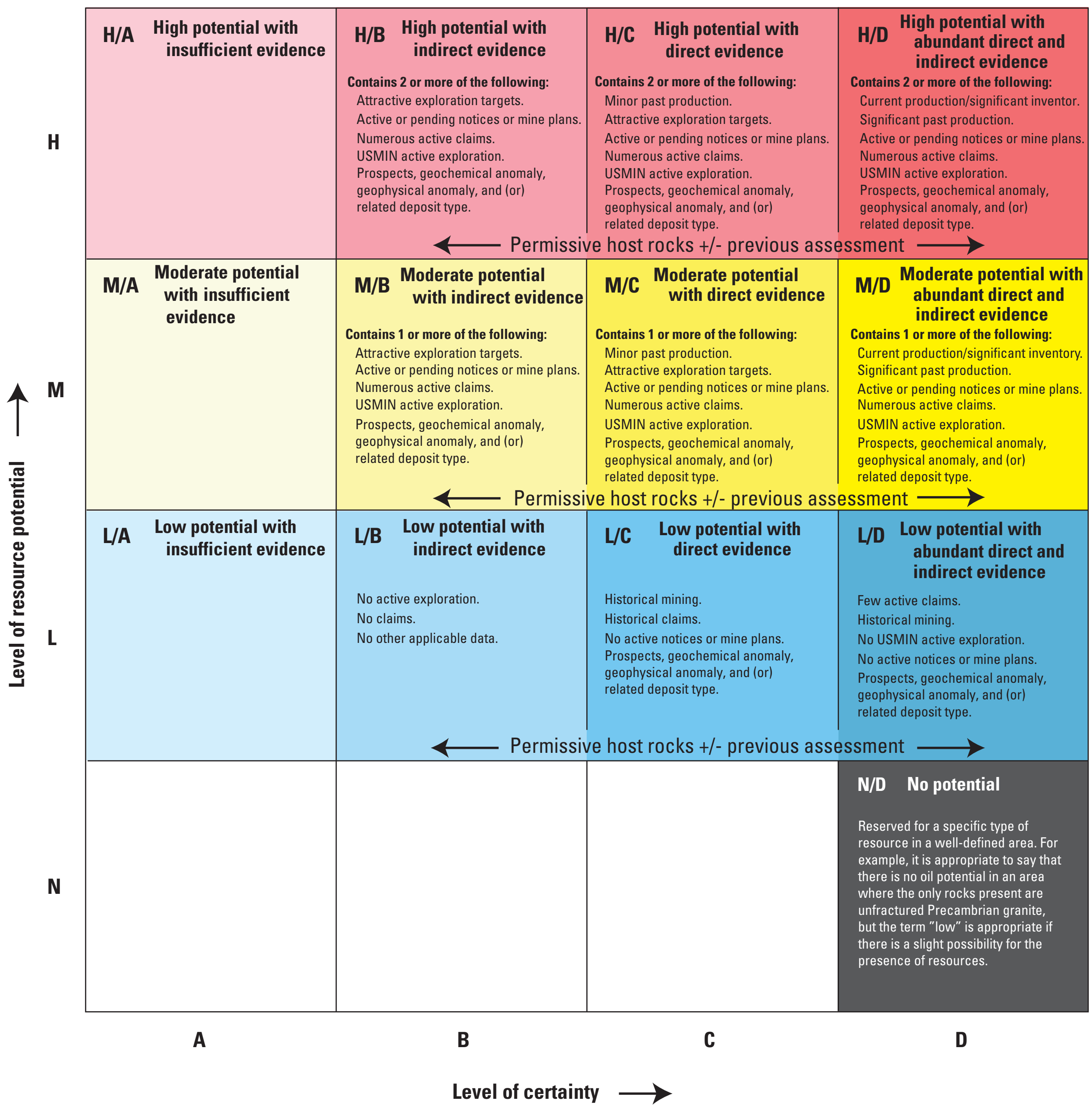


**Figure 1–1.** Matrix showing the classification system used for qualitative mineral-resource potential for locatable minerals in the Sagebrush Mineral-Resource Assessment (see text for abbreviations). USMIN, U.S. Geological Survey Mineral Deposit Database.

# Appendix 2. Table of Mineral-Potential Assessment Tracts for Locatable Minerals in the Southwestern and South-Central Wyoming Study Area, Wyoming, and Bear River Watershed Study Area, Wyoming and Utah

This appendix is available online only as an Excel (.xlsx) table at http://dx.doi.org/10.3133/sir20165089E. The table lists and summarizes characteristics of the mineral-potential assessment tracts for locatable minerals in the Southwestern and South-Central Wyoming study area, Wyoming, and Bear River Watershed study area, Wyoming and Utah.

# Appendix 3. Geochemical Samples for the Southwestern and South-Central Wyoming Study Area, Wyoming, and Bear River Watershed Study Area, Wyoming and Utah

[Of the 395 rock, 1,690 sediment, and 262 concentrate samples taken in the entire 25-kilometer buffered area around the USGS study areas, this table shows the number of samples within each subdivision (block),and those within the actual proposed withdrawal areas, and those within the greater PLSS study area]

| Southwestern and South-Central Wyoming Study Area, Wyoming | | | Bear River Watershed Study Area, Wyoming and Utah | | |
|---|---|---|---|---|---|
| **Subdivision (block)** | **Samples in study areas** | **Samples within proposed with-drawal area** | **Subdivision (block)** | **Samples in study areas** | **Samples within proposed with-drawal area** |
| Concentrate samples | | | | | |
| South Pass, Wyoming | 92 | 1 | Fontenelle, Wyoming | 0 | 0 |
| Big Sandy, Wyoming | 0 | 0 | Fossil Basin, Wyoming | 0 | 0 |
| Continental Divide, Wyoming | 0 | 0 | Bear Lake Plateau, Utah | 0 | 0 |
| Boars Tusk, Wyoming | 0 | 0 | | | |
| **Total** | **92** | **1** | | **0** | **0** |
| Rock samples | | | | | |
| South Pass, Wyoming | 24 | 0 | Fontenelle, Wyoming | 1 | 1 |
| Big Sandy, Wyoming | 5 | 0 | Fossil Basin, Wyoming | 1 | 0 |
| Continental Divide, Wyoming | 0 | 0 | Bear Lake Plateau, Utah | 5 | 0 |
| Boars Tusk, Wyoming | 0 | 0 | | | |
| **Total** | **29** | **0** | | **7** | **1** |
| Sediment samples | | | | | |
| South Pass, Wyoming | 48 | 11 | Fontenelle, Wyoming | 75 | 20 |
| Big Sandy, Wyoming | 63 | 20 | Fossil Basin, Wyoming | 88 | 7 |
| Continental Divide, Wyoming | 5 | 1 | Bear Lake Plateau, Utah | 18 | 1 |
| Boars Tusk, Wyoming | 18 | 2 | | | |
| **Total** | **134** | **34** | | **181** | **28** |

# Appendix 4. Table of Oil and Gas Plays and Assessment Units in the Southwestern and South-Central Wyoming Study Area, Wyoming, and Bear River Watershed Study Area, Wyoming and Utah

This appendix is available online only as an Excel (.xlsx) table at http://dx.doi.org/10.3133/sir20165089E. The table relates Public Land Survey System (PLSS) townships to U.S. Geological Survey (USGS) reports on oil and gas resource assessments for assessment units or plays in the Southwestern and South-Central Wyoming Sagebrush study area, Wyoming, and Bear River Watershed Sagebrush study area, Wyoming and Utah. If an assessment was conducted in 1995, then the terminology used was "play." After 1995, the terminology became "assessment unit" (AU). In many cases, more than one play or AU may be present within a given PLSS township. The table lists each PLSS township and the associated play or AU, the name of the play or AU, the related USGS publication title, and a link to the published USGS geologic assessment report. The USGS reports include many additional details regarding the source rocks, reservoir rocks, type of trap, reservoir properties, and resource potential.

# Appendix 5. Table of Producing Properties in Southwestern Wyoming and Northeastern Utah

This appendix is available online only as an Excel (.xlsx) table at http://dx.doi.org/10.3133/sir20165089E. The table lists all producing properties in the counties that contain parts of the Southwestern and South-Central Wyoming study area, Wyoming, and Bear River Watershed study area, Wyoming and Utah. This list is derived from a 2011 database of producing properties in the western U.S. from the National Minerals Information Center (Robert Callaghan, written commun., March 7, 2016) and supplemented with data from the U.S. Forest Service (Roger Kesterson, U.S. Forest Service, written commun., March 11, 2016) for properties that are in the Bear Lake Plateau block. Only 13 of the 63 properties are within the study areas, and 3 of those are within the proposed withdrawal area.

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