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Geology and Mineral Resources of the North-Central Montana Sagebrush Focal Area

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

Scientific Investigations Report 2016–5089–D

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

Cover. Photograph of a low, dark-colored bench, the outcrop expression of a bentonite bed, in north-central Montana (U.S. Geological Survey photograph by Michael L. Zientek).

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Edited by Warren C. Day, Thomas P. Frost, Jane M. Hammarstrom, and Michael L. Zientek

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

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

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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
$°F = (1.8 \times °C) + 32$.

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	$ZrSiO_4$

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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 effects of locatable mineral exploration and mining. To inform the decision on whether to withdraw the SFAs from mineral entry, the Bureau of Land Management (BLM) requires a mineral-resource assessment be completed to identify mineral resources within the proposed area of withdrawal. 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 summarizes the current status of locatable, leasable, and salable mineral commodities and assesses the potential of locatable minerals in the North-Central Montana Focal Area.

The proposed withdrawal area that is evaluated in this report is located in north-central Montana, and includes parts of Fergus, Petroleum, Phillips, and Valley Counties. The proposed withdrawal area encompasses 3,545 km^2 (876,036 acres), of which, the BLM manages 3,430 km^2 (847,571 acres).

The study area is along both sides of the Missouri River, in the Northern Great Plains physiographic province. The Little Rocky Mountains are just outside the northwestern part of the study area, and the Judith Mountains are nearby, to the southwest of the study area.

The vast majority of the study area is underlain by sedimentary rocks. The Cretaceous Bearpaw Shale is the most widespread formation; it crops out over most of the study area, and younger Cretaceous to Paleocene sedimentary rocks crop out locally in the southeastern part of the study area. Pleistocene glacial deposits are found locally in the study area, predominantly in the northern part, and Quaternary deposits are widespread in river and stream valleys.

The Little Rocky Mountains host Cretaceous to Paleocene alkaline intrusive rocks that have domed and uplifted the older sedimentary rocks that they intruded. The study area also includes part of the Missouri River Breaks diatremes, which are Eocene mantle-derived alkaline ultramafic diatremes and dikes.

Mining and Mineral Activity in the Area

The focal area does not appear to contain significant concentrations of leasable minerals. However, there has been production of locatable and salable minerals from the study area, and there is further potential for these in the focal area.

Leasable

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. Oil shale, native asphalt, sodium, potash, potassium, and sulfur do not occur in significant concentrations within or near the study area.

There are no coal or geothermal leases in the proposed withdrawal area, and there are 16 non-energy solid mineral leases in the proposed withdrawal area, all of which are closed. Owing to the thinness, lack of lateral continuity, poor quality, and depth of cover, the coal beds in the study area are not likely to generate economic interest in the future. There are no known moderate- to high-temperature geothermal systems in the area, and the area does not have significant enhanced geothermal systems potential.

There are 1,133 oil and gas leases in the proposed withdrawal area; all but five of these are closed. There has not been any significant hydrocarbon production within the study area, and the overall potential appears to be low.

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 of lode or placer mining claims. Locatable minerals include metallic minerals, industrial minerals, and uncommon varieties of sand, gravel, stone, pumice, pumicite, and cinders. Based on the geology of the study area, and past production in the study area and nearby, the study area has potential for gold, silver, bentonite, and diamonds.

Gold and silver may occur in epithermal gold-silver deposits and placer gold deposits. The Zortman and Landusky epithermal deposits in the Little Rocky Mountains outside the study area produced 2.5 million troy ounces (oz) of gold (78 metric tons [t]) and 20.7 million oz of silver (644 t), but the igneous rocks that host these deposits are exposed in only a small part of the northwestern part of the study area, and there has been no significant production from epithermal deposits in the study area. Available geological, geochemical, and geophysical data indicate that the potential for epithermal deposits in the study area is low.

Placer gold deposits occur downstream of some hard rock gold deposits, but historic production of gold from placer deposits in the Zortman-Landusky District was reportedly only 326 oz of gold (10 kg), which is insufficient for any modern, large-scale placer operation. Furthermore, the gold in the hard rock deposits occurs predominantly in solid solution in pyrite and in telluride minerals. Gold in these minerals is not recoverable by conventional placer operations. Available data indicate that the potential for gold placer deposits in the study area is low, and there are no gold placer tracts in the proposed withdrawal area.

Bentonite exploration and mining activity has been ongoing in the study area for at least 60 years. More than 1.7 Mt of bentonite has been produced from small open pits near Glasgow and Malta. There are two pending plans of operations for bentonite in the proposed withdrawal area and one approved plan of operations. Predictive models developed in this report show that the study area contains approximately 280 km^2 (69,190 acres) where bentonite is potentially mineable because there are relatively thick bentonite beds that are at or near the surface. Approximately 124 km^2 (30,640 acres) of this high-potential area is in the proposed withdrawal area.

The Missouri River Breaks diatreme field partly overlaps the study area. Kimberlite-hosted diamond deposits in diatremes are one of the two main sources of diamonds from hard rock mines. However, in the study area, few of the diatremes are kimberlite, and the kimberlite diatremes lack indicator minerals that would suggest that they may contain diamond. Therefore, the potential for diamond deposits in the study area is low. There are no known kimberlites in the proposed withdrawal area, and therefore the potential for diamond deposits is low.

Salable

Salable minerals include sand and gravel, aggregates, dimension stone, petrified wood, cinders, clay, pumice, and pumicite. Sand and gravel have been produced in the study area, and there are also closed claims for petrified wood in the study area.

The sedimentary rocks that form the majority of the bedrock in the study area commonly contain abundant clay minerals, including bentonite. These minerals make the rock soft and crushable, and the clay minerals are expandable, so these rocks are not favorable sources for sand and gravel, which require hard, durable, chemically inert materials. Consequently, sand and gravel have predominantly been produced in the northern part of the study area, where glacial deposits with hard, durable materials are thickest.

The southern part of the study area contains a locality outside the proposed withdrawal area that appears to correspond to an occurrence of petrified wood in the Hell Creek Formation. However, the quality of petrified wood in the study area is low, and is not like the high-quality samples from southwestern Montana or Arizona. Furthermore, the lack of other claims in the study area, and the absence of previous assessments or citations in the published literature, suggest that significant resources of gem-quality petrified wood are unlikely to be present in the study area.

Introduction

The U.S. Department of the Interior "has approved an application to withdraw approximately 10 million acres of public and National Forest System lands identified as Sagebrush Focal Areas in Idaho, Montana, Nevada, Oregon, Utah, and Wyoming from location and entry under the United States mining laws to protect the Greater Sage-Grouse and its habitat from adverse effects of locatable mineral exploration and mining, subject to valid existing rights" (U.S. Department of the Interior, 2015a). A withdrawal does not affect valid existing rights. The lands proposed for withdrawal are part of the seven Sagebrush Focal Areas (Bureau of Land Management, 2015b, c).

The purpose of this report is to summarize the current status of locatable, leasable, and salable mineral commodities and to assess the potential of locatable minerals in the North-Central Montana Focal Area in Montana. This report was prepared as required by the Federal Land Policy and Management Act of 1976, 43 U.S.C. 1701–1785 (FLPMA), for an application for withdrawal of lands. This report follows guidance provided in BLM Manual Sections 3031 and 3060 (Bureau of Land Management, 1985, 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.

Lands Involved

This report describes the mineral potential of the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area. The proposed withdrawal area is located in Montana, and includes parts of Fergus, Petroleum, Phillips, and Valley Counties. The proposed withdrawal area encompasses 3,545 km^2 (876,036 acres), of which, the BLM manages 3,430 km^2 (847,571 acres; fig. 1). The study area, which encompasses 10,424 km^2 (2,575,704 acres), is made up of all the townships that include areas proposed for withdrawal. The townships include those first described by the BLM (Bureau of Land Management, 2015d), as formally proposed by the U.S. Department of the Interior (2015a, b), and further amended by the BLM through correspondence (Anthony Titolo, BLM, written commun., April 22, 2016). The adjacent Public Land Survey System (PLSS) township boundaries were dissolved to define the study area and then modified to exclude Native American lands, which are sovereign and exempt from withdrawal.

The BLM LR2000 database shows 2,177 mining claims in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area; 1,490 of these are closed and the remaining 687 are active (table 1). These are described more fully in the Locatable Minerals section of this report. There are no coal or geothermal leases in the proposed withdrawal area, and there are 16 non-energy solid mineral leases in the proposed withdrawal area, all of which are closed. There are 1,133 oil and gas leases in the proposed withdrawal area; all but five of these are closed (table 1). There are 15 mineral materials sales sites in the proposed withdrawal area; one of these is authorized, and the rest are closed or expired. As discussed in the Salable Minerals section of this report, these relate to sand and gravel operations. There are eleven 43 CFR 3809 notices and plans of operations in the proposed withdrawal area, and, as discussed in the Locatable Minerals section of this report, these all relate to bentonite.

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, we organized the information in this report to reflect BLM technical and legal language and use the legal classification of minerals recognized by BLM. Potential for occurrence is only discussed for locatable minerals.

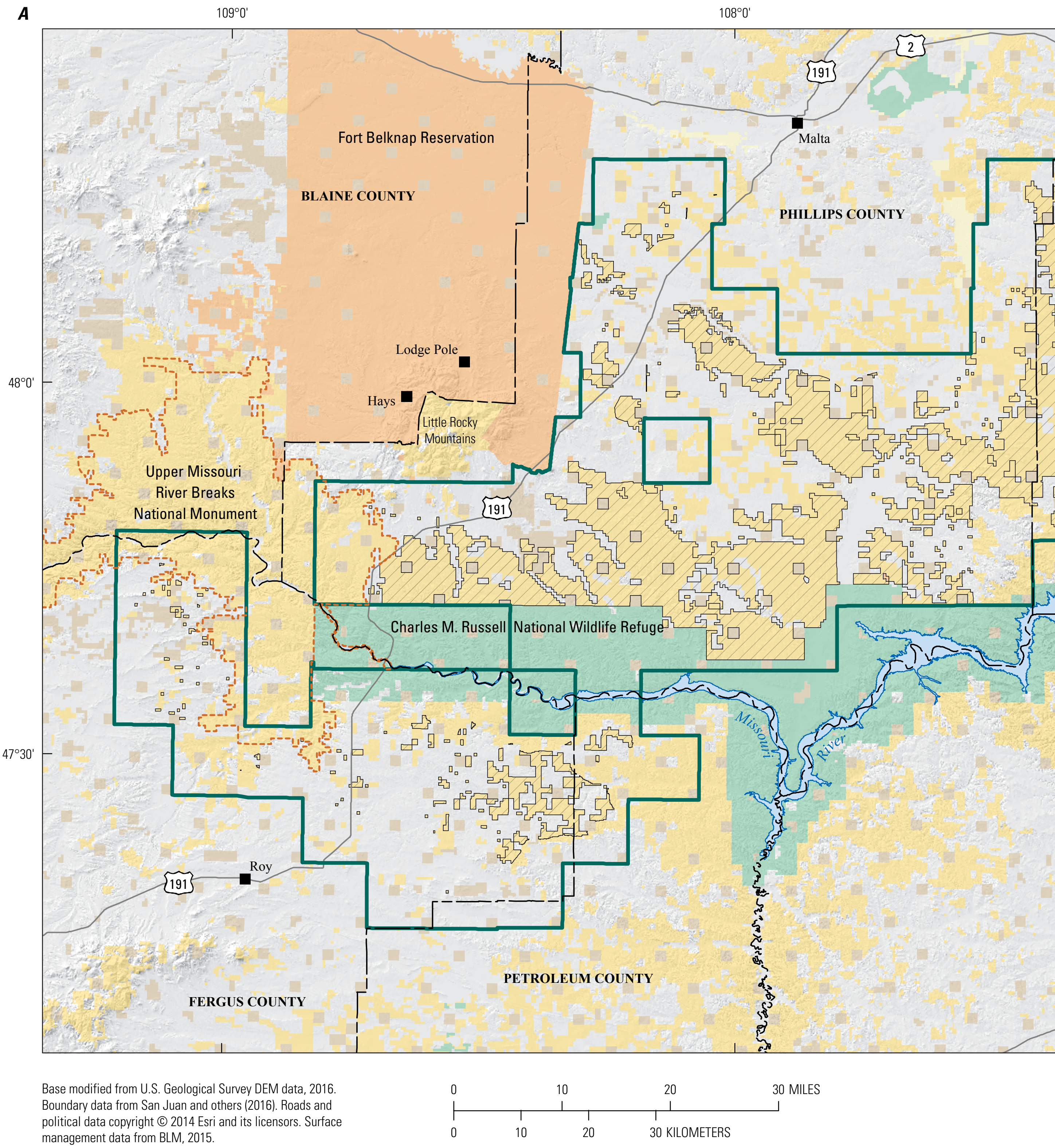
Several schemes are used to classify types of minerals in scientific and technical literature. For example, a distinction is made between materials from which metals are extracted (metallic) and those that are not used as a source of metal or energy (nonmetallic or industrial). Another scheme differentiates 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 laws 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 General Mining Act of 1872, 30 U.S.C. 22–54, as amended. Locatable minerals include materials from which metallic and nonmetallic minerals are mined, industrial minerals, and certain varieties of mineral materials if they are uncommon because they possess a distinct and special value. Leasable minerals for Federal lands or a federally retained mineral interest in lands in the United States refer to commodities acquired through the Mineral Leasing Act of 1920 (30 U.S.C. 181 et seq.), as amended; the Geothermal Steam Act of 1970 (30 U.S.C. 1001 et seq.), as amended; or the Mineral Leasing Act for Acquired Lands of 1947 (30 U.S.C. 351 et seq.), 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 et seq.), 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 comply with surface-management regulations (43 CFR 3809). Table 1 summarizes information on mining claims, leases, and salable mineral sites, along with surface-management (43 CFR 3809) authorizations in the Focal Area.

The mining laws applicable to Federal lands of the United States were not developed with specific knowledge of geology or 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, bedded deposits of soluble sodium and potassium salts, and bedded deposits of phosphorite. Salable minerals are common earth materials that are widely distributed and have 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



Base modified from U.S. Geological Survey DEM data, 2016. Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors. Surface management data from BLM, 2015.
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983.

Figure 1. Surface land management map of the North-Central Montana Sagebrush Focal Area. BLM, Bureau of Land Management; USGS, U.S. Geological Survey.

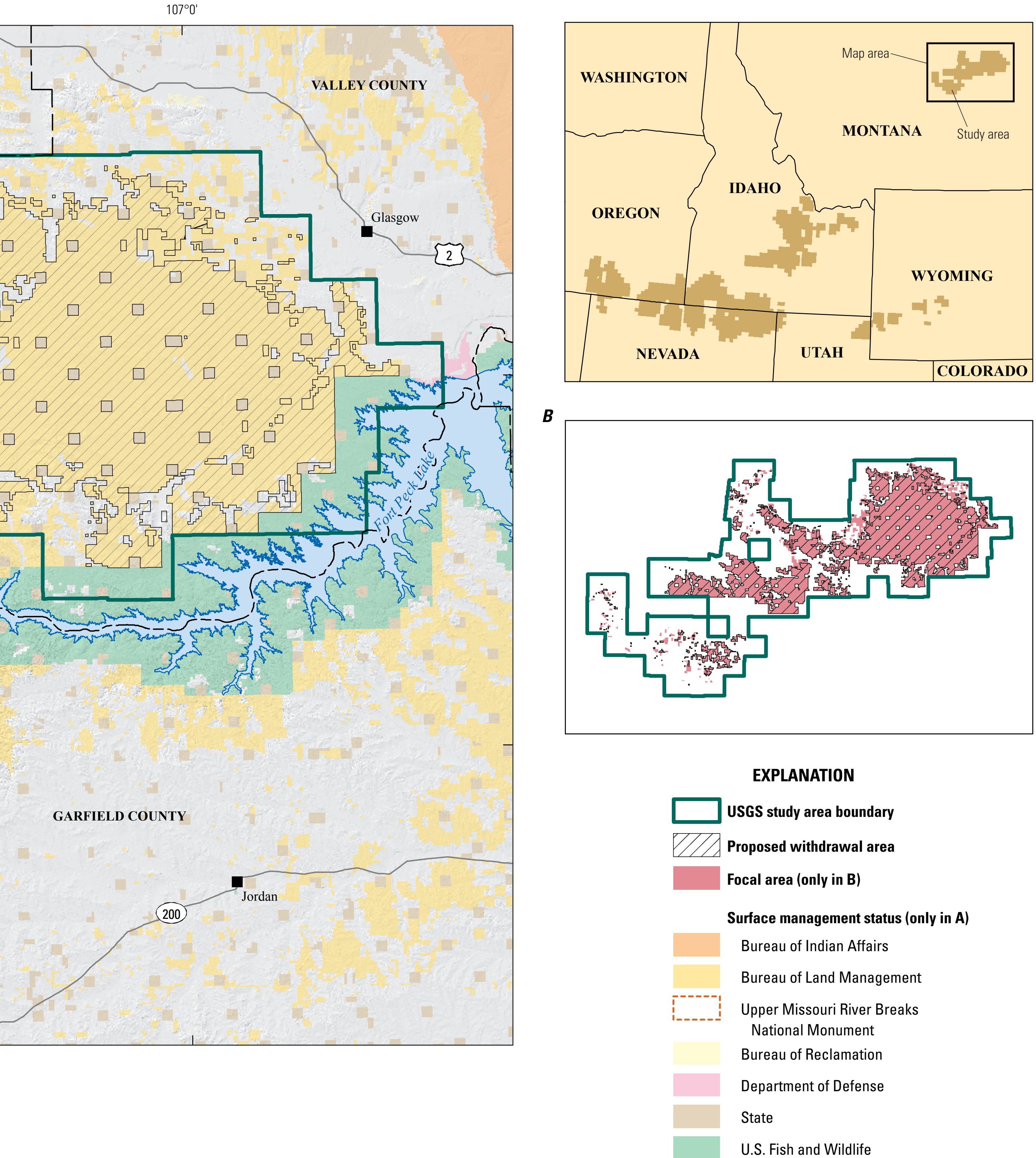

107°0'
VALLEY COUNTY
Glasgow
2
Fort Peck Lake
GARFIELD COUNTY
Jordan
200
WASHINGTON
OREGON
IDAHO
MONTANA
Map area
Study area
NEVADA
UTAH
WYOMING
COLORADO
B
EXPLANATION
USGS study area boundary
Proposed withdrawal area
Focal area (only in B)
Surface management status (only in A)
Bureau of Indian Affairs
Bureau of Land Management
Upper Missouri River Breaks National Monument
Bureau of Reclamation
Department of Defense
State
U.S. Fish and Wildlife

Table 1. Status and number of mining claims, mineral leases, mineral material sales sites, and 43 CFR 3809 notices and plans of operations in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area.

[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]

Type	Mineral type	Number of unique cases	Active	Autho-rized	Pending	Closed	Cancelled	Expired	Rejected	With-drawn
Mining claims	Locatable	2,177	687	ND	ND	1,490	ND	ND	ND	ND
Coal leases	Leasable	0	ND	ND	ND	ND	ND	ND	ND	ND
Geothermal leases	Leasable	0	ND	ND	ND	ND	ND	ND	ND	ND
Non-energy solid mineral leases	Leasable	16	ND	ND	ND	16	ND	ND	ND	ND
Oil and gas leases	Leasable	1,133	ND	ND	5	1,128	ND	ND	ND	ND
Mineral materials sales sites	Salable	15	ND	1	ND	11	ND	3	ND	ND
Surface-management plans	Locatable	11	ND	1	2	8	ND	ND	ND	ND

In this report, we use three terms to refer to the area under investigation: (1) Focal Area, (2) study area, and (3) proposed withdrawal area.

1. The Sagebrush Focal Areas have been identified by the BLM and the U.S. Forest Service as important landscape blocks with high breeding-population densities of sage-grouse and existing high-quality sagebrush. The North-Central Montana Sagebrush Focal Area is the term used for the identified Focal Area that is the subject of this report.

2. Because the lands that are within the Focal Area have complex boundaries, the *study area* has been expanded outward from the Focal Areas to the nearest survey township boundary, where each survey township is a square parcel of land of 36 mi^2 (93.2 km^2). This simplifies the approach from a geological basis, because it allows us to examine a large, relatively contiguous block of land.

3. For the Sagebrush Focal Areas, the *proposed withdrawal areas* are a subset of the Focal Areas, so some parts of the Focal Areas are proposed for withdrawal, and other parts are not.

In this report, we use *Focal Area* for the titles of figures and tables to show the link with the Sagebrush Focal Areas that have been identified by the BLM and the U.S. Forest Service. In most of the text, and within the figures, we focus on the *study area* and the *proposed withdrawal areas*. The former provides the larger perspective that is most useful for evaluating the geological, geochemical, geophysical, and remote sensing data that underpin our work (Anderson and Ponce, 2016; Rockwell, 2016; Smith and others, 2016), and that together provide the foundations for our resource assessments. The *proposed withdrawal areas* can then be compared with the larger scale evaluations that we describe within the *study area*.

A glossary of terms is provided in Day and others (2016). 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 conform to the legal definitions that determine their ownership and development. However, for other terms, such as "minerals", the intended meaning must be inferred from context.

Who Did the Work?

This report represents contributions from a multidisciplinary team of U.S. Geological Survey (USGS) geologists, geophysicists, geochemists, mineral commodity specialists, and geographic information system (GIS) experts. These geoscientists reached out to personnel from the Montana Bureau of Mines and Geology, the BLM in Montana, and the Montana Department of Environmental Quality to gather the most recent information on geology and mineral resources. Representatives from these groups also provided helpful feedback on the preliminary tracts that we developed for the study area.

Jeffrey L. Mauk, Michael L. Zientek, and B. Carter Hearn, Jr., wrote the majority of the text in this report, and Michael L. Zientek created the outline used for the project when preparing the assessment reports. Heather L. Parks and M. Christopher Jenkins undertook much of the GIS work that underpins this report, including working with others to create most of the tracts in this report, and Heather produced the figures.

For the assessment of locatable minerals, Jeffrey L. Mauk took the lead for assessing gold potential in epithermal and placer deposits with assistance from Stuart A. Giles and Heather L. Parks (GIS support and tract creation). Eric Anderson modeled depth-to-source of geophysical anomalies to determine if any could represent shallow intrusions that may host epithermal deposits. Michael L. Zientek was primarily responsible for the bentonite assessment, with Heather L. Parks and M. Christopher Jenkins compiling data, interpreting satellite imagery, and doing geospatial calculations for the assessment. B. Carter Hearn, Jr., evaluated diamond potential in the study area with assistance from Eric D. Anderson (interpretation of aeromagnetic data for unmapped diatremes), Heather L. Parks (GIS support, tract creation, and writing), and Michael L. Zientek (GIS support, tract creation, and writing).

The Leasable Minerals section of this report was produced by several authors: Douglas B. Yager wrote the Potash section; Brian N. Shaffer and Jon E. Haacke wrote the Coal section; Colin F. Williams, Jonathan M.G. Glen, and Jacob DeAngelo wrote the Geothermal section; Ronald M. Drake II wrote the Oil and Gas section; and Mary Ellen Benson worked together with Jeffrey L. Mauk to write the Phosphate section.

The Salable Minerals section was put together by Jeffrey L. Mauk with assistance from Heather L. Parks (GIS support and figure creation). Joyce A. Ober provided thoughtful, timely, and valuable feedback that helped improve this section of the report.

Connie L. Dicken compiled and delivered information from the BLM, which included information on locatable, leasable, and salable commodities. She provided the summary tables required for the report and synthesized the BLM data spatially so it could be used in the assessment. Her work guided our analysis of what commodities should be assessed, and provided some level of validation when we created our mineral potential maps.

Paul D. Denning, Stuart A. Giles, John D. Horton, and Carma A. San Juan provided assistance with GIS at various critical points in the project. Eric D. Anderson compiled the geophysical results in this report, and worked with us to use legacy data in novel ways to help inform the assessment for metallic and non-metallic minerals. Helen W. Folger, Matthew Granitto, Karen D. Kelley, and Steven M. Smith compiled the geochemical data that underpin parts of this report, provided specialty databases, reviewed and commented on parts of this report, and provided deep insight into the interpretation of the geochemical data in the study area. Barnaby W. Rockwell provided expert knowledge of remote sensing data, which helped to inform and validate the tracts for bentonite. Donald I. Bleiwas and Elizabeth S. Sangine contributed commodity information and expertise, and Don provided helpful feedback on our preliminary tracts. Gregory L. Fernette and Peter N. Schweitzer made available the USGS Mineral Deposit Database project (USMIN) and the Mineral Resources Data System (MRDS), and Greg provided helpful discussions about past production and possible resources in the study area.

Description of Geology

This section describes the physiography and geology of the study area and nearby.

Physiography and Ecoregions

The study area is in north-central Montana, along both sides of the Missouri River, in the Northern Great Plains physiographic province (fig. 2). The study area is close to the Little Rocky Mountains on the northwest, and close to the Judith Mountains on the southwest. Havre, Montana, is about 180 km to the northwest and Lewistown, Montana, is about 120 km to the southwest. Access to the study area can be difficult because most of the roads are unimproved tracks across sedimentary rocks that contain bentonite—a soft clay mineral with the ability to absorb large quantities of water and change volume. A small amount of rain may immobilize even four-wheel drive vehicles.

Dominant topographic features include flat-top ridges and plateaus, cut by winding coulees, many of which are precipitously steep and narrow, although some have broad flood plains. Elevations range between 1,400 and 600 m. All streams in the area are intermittent and discharge into the Missouri River or the Milk River (fig. 2). Temperatures may exceed 40 °C in the summer and drop below −40 °C in the winter. Thunderstorms are common from spring through fall, accompanied by winds that occasionally exceed 60 km per hour. A thin snow cover persists during the winter and spring months, but accumulation may be more than 1 m deep after large storms.

The study area contains three level III ecoregions: the Middle Rockies, the Northwestern Glaciated Plains, and the Northwestern Great Plains (Woods and others, 2002). A small part of the Scattered Eastern Igneous Core Mountains subdivision of the Middle Rockies ecoregion extends south into the study area from the Little Rocky Mountains. This subdivision is mostly wooded and, though dry, receives more precipitation (40 to >80 cm annually) than other parts of the study area. Two subdivisions of the Northwestern Glaciated Plains are present in the study area: the Glaciated Northern Grasslands cover most of the northern part of the study area, and the Foothill Grasslands surround the Little Rocky Mountains in the northwest. The Glaciated Northern Grasslands is a divided plain dominated by rangeland, with agriculture taking place on intermittent gravel benches and on the Milk River Valley's irrigated alluvial soils. The Foothill Grasslands slope from the mountains in the northwest of the study area down to the plains, with sporadic hills and buttes cut by streams fed from the mountains; there is less precipitation there than in the mountains above, and more than in the plains below. Three subdivisions of the Northwestern Great Plains are present in the study area: the River Breaks in the southeastern part of the study area, the Missouri Breaks Woodland-Scrubland in the southwestern and south-central areas, and the Montana Central Grassland in the far southwestern as well as in the central-eastern areas. The River Breaks comprises a series of steeply eroded terraces and uplands that lead down into the Missouri and Yellowstone River systems below. The Missouri Breaks Woodland-Scrubland is similarly eroded, with clayey soils weathered from Cretaceous sedimentary rock (Woods and others, 2002).

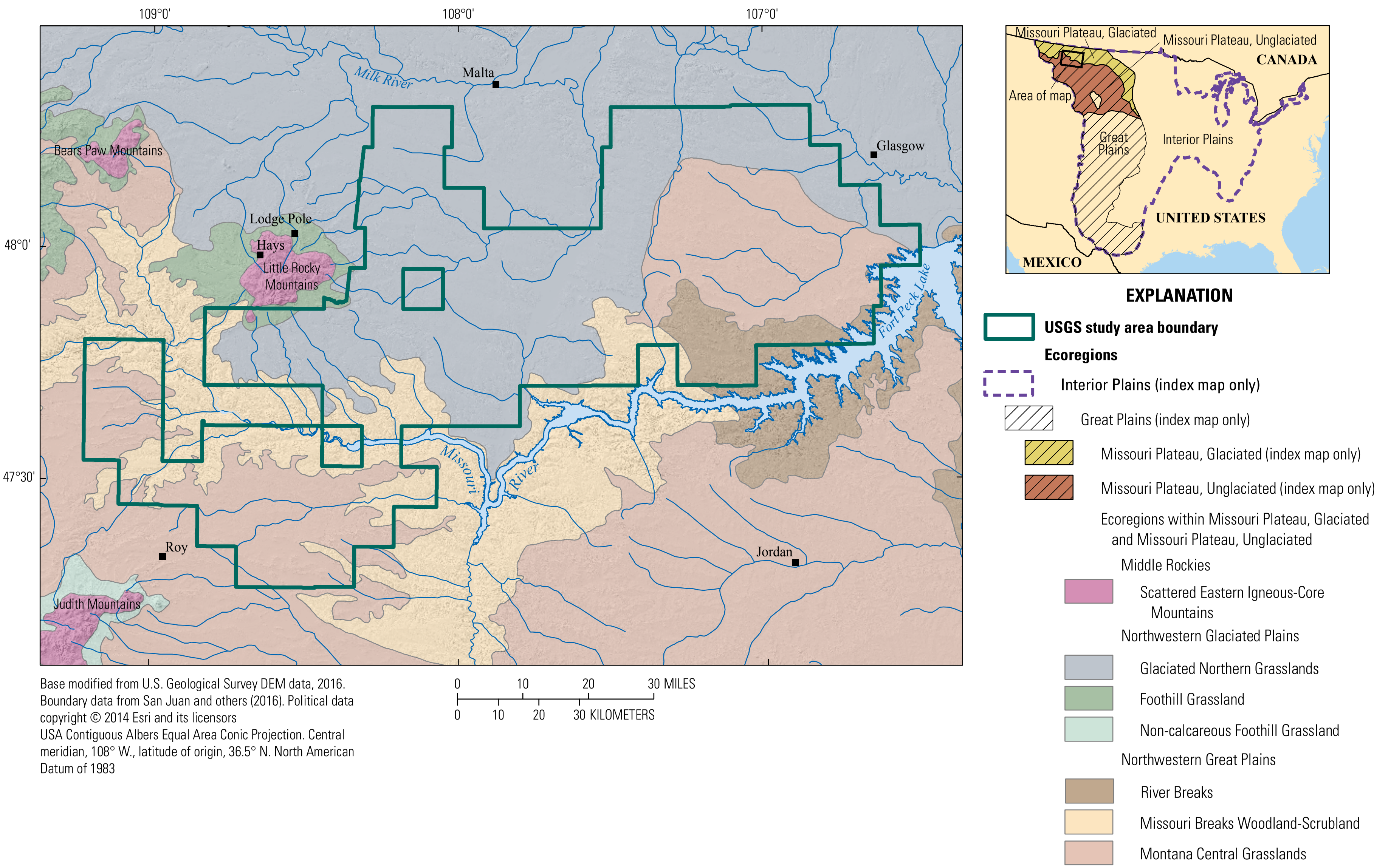


Figure 2. Map showing the physiographic ecoregions of the North-Central Montana Sagebrush Focal Area (modified from Trimble, 1980; Woods and others, 2002). USGS, U.S. Geological Survey.

Regional Geology and Tectonic Setting

Precambrian Basement Terranes

Most of the study area is underlain by the Wyoming Craton–Wyoming Province terrane of Archean age, at depths of about 1.5 km. Wyoming Craton metamorphic rocks are exposed in the Little Rocky Mountains as a result of uplift adjacent to and above Paleocene syenite porphyry intrusions (Knechtel, 1959). The Wyoming Craton terrane is bound to the northwest by the Great Falls Tectonic Zone (GFTZ) (fig. 3) and to the northeast by the north-northwest-trending Paleoproterozoic Trans-Hudson orogen/Dakota domain. These are intracratonic mobile belts that transitioned into Paleoproterozoic suture zones, marking the collision of the Archean Medicine Hat block, the Archean Wyoming craton, and the Archean Superior terrane (for example, Mueller and others, 2005; Lund and others, 2015, and references therein; fig. 3*A*). East of the Rocky Mountain front in Montana, the GFTZ is entirely concealed by Paleozoic and Mesozoic sedimentary rocks, has been approximately defined by geophysical anomalies, and shows no northeast-trending faults in surface exposures. The GFTZ is shown with various trends and widths in recent publications (in other words, N. 25° E., 65 km wide, Gorman and others, 2002; N. 55° E., 90 km wide, Carlson and others, 2004; N. 50° E., 135 km wide, Barnhart and others, 2012). In the Wyoming Craton, GFTZ, and southern part of the Medicine Hat block, seismic profiles show that the crust is abnormally thick, as much as 60 km, and the lower crust consists of 10–30 km of dense, high-velocity 7.0–7.8 km/s material (Gorman and others, 2002). On a different scale, past studies have inferred separate Precambrian basement blocks on the basis of contrasting aeromagnetic and gravity patterns, with inferred block boundaries between areas of contrasting orientation of parallel magnetic anomaly patterns, or where such parallel patterns end against areas without any preferred anomaly orientation (Zietz and others, 1968; Zietz and others, 1980).

Isotopic age data show additional complexities of the terranes and collision zones. Margins of Archean cratons have been affected by younger Paleoproterozoic metamorphic events in the 1.8–1.7 Ga range, whereas U-Pb zircon ages show evidence for Archean ancestry (Davis and others, 1995). Exposed Precambrian felsic gneisses and mafic amphibolite in the Little Rocky Mountains have Archean Rb/Sr isochron ages but have biotite and amphibole K/Ar ages in the 1.8–1.1 Ga range (Peterman, 1981). Age data for monazites in deep crustal xenoliths show multiple Paleoproterozoic and Mesoproterozoic metamorphic events (Barnhart and others, 2012).

Xenoliths of lower crustal mafic and felsic granulites from dikes, plugs, and diatremes provide age data for the underlying concealed Precambrian basement. Xenoliths from the southeastern Bears Paw Mountains localities record a series of heating events at 2.2–2.1 Ga, 1.5 Ga, and 1.3 Ga, whereas zircon cores have $^{207}Pb/^{206}Pb$ ages of 3.0–2.5 Ga (Barnhart and others, 2012). Xenoliths from the Archean Medicine Hat block show dates of ~1.8 Ga and neodymium isochron dates of 1.7–1.5 Ga, representing reheating of Archean crust or Proterozoic additions to the lower crust (Davis and others, 1995; Irving and others, 1997; Gifford, 2015).

Structure

Most of the study area and surrounding region show bedding with low-angle dips in outcrops, owing to gentle monoclinal flexures, anticlines, and synclines in the exposed Mesozoic and Paleocene sedimentary formations (fig. 3*B*). The eastern part of the study area is on the western flank of the Williston Basin (fig. 3). Formations are strongly uplifted around and above intrusions in the Little Rocky Mountains and Judith Mountains, which each contain closely spaced intrusions that produced a series of nested, coalescing domes (fig. 4).

In central and south-central Montana, several subparallel, en-echelon fault zones trending N. 70–80° W. reflect buried Precambrian basement faults (figs. 3, 4, though owing to their lack of surface exposure, none of the faults are labeled or described on the maps). From north to south are the Cat Creek fault zone (lineament), a poorly developed zone east-southeast of Grass Range, the Devils Basin–Big Wall anticlinal trend, and the Lake Basin fault zone. Some fault zones have been repeatedly active from the Proterozoic to the Mesozoic, controlling deposition, facies, source rocks, and accumulations of oil and gas. The Cat Creek fault zone and the Lake Basin fault zone have been the north and south boundaries of the Central Montana Trough depositional basin (fig. 3; Norwood, 1965). The Cat Creek fault zone at depth extends at least to longitude 110° W. based on subsurface data, showing offset of Mississippian and Devonian beds (southwest side down) at 1,500 m below mean terrain elevation (Culver, 1982). The Cat Creek fault zone approximately marks the northern boundary of the eastward depositional salient of the Proterozoic Belt Supergroup (Winston, 1986). In the Mesozoic, much of the Central Montana Trough was uplifted (referred to as the Central Montana Uplift or Central Montana Platform), with the development of an east-southeast band of folds and domes (Norwood, 1965).

Other prominent faults are in the N. 45–55° E.-trending, 200-km-long Weldon–Brockton–Froid fault zone, which lies to the east and southeast of the study area (Colton and Bateman, 1956; Colton, 1963). Faults in the Weldon–Brockton–Froid zone have displaced Pleistocene glacial outwash deposits of late Wisconsin age, and alluvial-colluvial deposits and thus are relatively young (Colton and Bateman, 1956; Colton, 1963). Displacement of bedrock is as much as 60 m. A 40-km-long, N. 65° W.-trending fault zone bounds the northeast side of Freedom Dome, which is 20 km south of Jordan and south of the study area. Within the study area, 1:100,000-scale geologic maps show shorter normal faults and fault zones that trend ~N. 45° E., and fewer short 1–3-km-long normal faults trending N. 30–60° W. These faults displace Upper Cretaceous and Paleocene beds about 6 to 30 m (Porter and Wilde, 1993, 2001; Wilde and Bergantino, 2004a, b).

Southwest of the Little Rocky Mountains, the western part of the study area contains remarkable, complex shallow gravity-slide structures (fig. 4). The Missouri River Breaks are crossed by many long fold-and-fault structures. These fold-and-fault structures are due to gravity sliding of the middle Eocene Bearpaw Mountains volcanic pile off of a central east-west antiformal uplift (Bearpaw Mountains arch) containing multiple intrusion-cored domes, sills, and dikes (Hearn, 1976). The gravity slides also involved the underlying pre-volcanic Upper Cretaceous, Paleocene, and lower Eocene sedimentary formations. The deepest slide plane typically is in or near the Cretaceous Greenhorn Formation, but locally is deeper, in the Cretaceous Mowry Shale. The volcanic pile and subjacent sedimentary formations slid northward on the north side of the arch and slid southward on the south side of the arch. In the headward-proximal zones of the detachment sheets, pull-apart graben structures developed, with volcanic rocks and pre-volcanic formations down-faulted as large tilted blocks or half grabens. In the distal zone across much of the Missouri Breaks, the sliding sheets locked, folded, and broke, forming reverse-fault antiformal structures approximately 1–2 km wide, spaced 3–5 km apart, with intervening zones of nearly horizontal sedimentary formations. Based on geophysical drill hole logs, distinctive marker beds below the basal slide plane show dips of 5–20 m per kilometer (Hearn, 1976).

The fold-and-fault zones of the gravity-slide complex can have three structural types: circumferential, radial, and oblique, based on their geometry in plan view, relative to the approximately circular area of the Bears Paw Mountains.

1. Structures circumferential to the Bears Paw Mountains are faulted folds that contain reverse faults and show the results of compression in the slide sheets.

2. Structures radial to the Bears Paw Mountains are tear faults that probably have strike-slip displacement, but the amount of strike-slip offset is difficult to document because there are no offset markers. The radial tear faults mark boundaries between separate gravity-slide sheets. Thus, on each side of such radial fault zones, circumferential faulted folds probably developed independently and cannot be correlated as lateral offsets. Tear faults may show zones of folding and uplift, but those zones are generally narrower than in circumferential structures.

3. Structures that are oblique (neither circumferential nor radial) show characteristics of both circumferential and radial faults. The oblique structures can change along strike from faulted-fold type, to narrow zones of steeply dipping faults that contain thin slices of uplifted formations.

The timing of the uplift, volcanism, and gravity sliding in the Bears Paw Mountains area is uncertain. The span of volcanism is 53 to 49 Ma by conventional K/Ar techniques (Marvin and others, 1980), with some supporting paleomagnetic data. In the lowermost Bearpaw Mountains volcanic rocks, local mafic or mixed mafic-felsic pyroclastic deposits are involved in down faulting that is probably related to early gravity sliding. The youngest units of the Bearpaw Mountains volcanic rocks apparently are unconformable over earlier volcanic rocks, but are also faulted and tilted along the border of the arch. All of the diatremes and associated dikes in the Missouri Breaks area are younger than the gravity sliding, based on crosscutting relations. Conventional K/Ar ages of the diatremes and dikes are 52 to 47 Ma, which is slightly younger than Bears Paw Mountains igneous activity (Marvin and others, 1980). Several diatremes contain pebbles and cobbles of Bearpaw Mountains intrusive and volcanic rocks, and one, the Lone Tree Ridge diatreme, contains down-faulted slices of clastic outwash deposits derived from erosion of the Bearpaw Mountains volcanic rocks. These clastic deposits are conglomeratic sandstones that contain pebbles of mafic phonolite and latite, and contain distinctive clasts of mafic analcime phonolite, porphyritic syenite, and tinguaite from the two youngest series in the Bears Paw Mountains. The sand-size fraction is rich in dark green augitic clinopyroxene, typical of present-day stream sediments coming from the Bearpaw Mountains volcanic fields (B. Carter Hearn, Jr., field observations).

Latest Cretaceous to Paleocene Intrusive Centers

Igneous rocks are mainly in two age groups: latest Cretaceous to Paleocene, and middle Eocene. Some outlying isolated intrusions are undated or are considerably younger, such as the Smoky Butte lamproite, which is dated at 27 Ma (Marvin and others, 1980; O’Brien and others, 1995).

Igneous rocks in the four intrusion-cored uplifts of the Little Rocky, Judith, and North and South Moccasin Mountains (fig. 3B) have ages from latest Cretaceous to Paleocene, 68 to 60 Ma. Igneous rocks generally are a sequence of syenite porphyries, quartz syenite porphyries, aegirine trachytes, or aegirine syenite porphyries. All four intrusion-cored uplifts have gold-silver mineralized areas of altered porphyries that are past producers. Skarn deposits are lacking or rare. In the Judith Mountains, three gold-silver-bearing skarn deposits occur in the Linster Peak dome in Mississippian limestone (Woodward, 1995). No skarn deposits are known in the Little Rocky or Moccasin Mountains (Weed and Pirsson, 1896; Wampler, 1994).

The intrusive sequence in the Little Rocky Mountains is quartz-phyric syenite porphyries, then syenite porphyries, followed by late aegirine trachyte and syenite porphyry dikes. The gold-silver mineralization is associated in part with the latest dikes (Wilson and Kyser, 1988; Rogers and Enders, 1990).

Middle Eocene Intrusive and Eruptive Centers

The Bears Paw Mountains, Highwood Mountains, Eagle Buttes, Little Belt Mountains, and Sweet Grass Hills (110 km west-northwest of Havre) are all middle Eocene in age, ranging from approximately 53 to 49 Ma (Marvin and others, 1973; Marvin and others, 1980). Only the Bears Paw and Highwood Mountains have volcanic flows and fragmental deposits, in addition to their intrusive equivalents. Known mineralization is minor compared to the Little Rocky, Judith, and Moccasin Mountains (Bateman and others, 1977; Bateman and Yamamoto, 1978).

Missouri Breaks Diatremes

The Missouri Breaks diatremes are named for the Missouri River Breaks, the intricately eroded badlands area along the Missouri River between Fort Benton and Fort Peck in north-central Montana where many of these bodies occur (fig. 2). These diatremes and associated intrusions provide evidence for mechanisms of eruption and emplacement of volatile-rich magmas, and demonstrate the genetic connections among melnoitic, kimberlitic, and carbonatitic magmas.

Diatremes and dikes produced by mantle-derived alkalic ultramafic magmas occur in a 140-km-long band that trends N. 80° E. from Haystack Butte on the southeast side of the Highwood Mountains to the southeast side of the Little Rocky Mountains (Hearn, 1968, 1979). Approximately 50 diatremes (including satellitic pipes) and 15 major dikes are concentrated in the eastern half of the band (fig. 3*B*). Additional undiscovered diatremes could be concealed by terrace gravels and glacial deposits in the western half of the band. Additional diatremes and dikes could be present beneath surficial deposits east of the Little Rocky Mountains, although existing geologic maps show no igneous features. Diatremes were emplaced between 52 and 47 Ma (Marvin and others, 1980), following most, if not all, of the igneous activity in the Bears Paw Mountains, Highwood Mountains, and Eagle Buttes. Many of the diatremes contain inclusions of peripheral down-faulted slices of early Eocene Wasatch Formation, and some contain clasts of some of the youngest intrusive rocks (51 to 49 Ma) of the Bearpaw Mountains igneous complex. Some diatremes cut across the distal faults and folds in the gravity-slide sheets.

The dominant trends of dikes, and of some groups of three to four diatremes, are from about N. 60° E. to N. 45° E., more northerly than the N. 80° E. overall trend of the band. These dike trends probably reflect only the shallow stress patterns and fracture alignments within the gravity-slide sheets, normal to the dominant directions of movement (S. 30° E. to S. 45° E.). However, the overall N. 80° E. trend of the band of diatremes represents a major zone of access of deep-source magmas, and thus indicates the deeper stress field and trend of a zone of weakness in the lithosphere. This trend differs somewhat from aeromagnetic trends (N. 30–60° E., Zietz and others, 1980) and gravity anomaly trends (Peterson and Rambo, 1967; Smith, 1970) in the Precambrian basement terrane, as well as from trends of major tectonic lineaments (Thomas, 1974; O'Neill and Lopez, 1985).

Stratigraphy

The vast majority of the study area is underlain by sedimentary rocks. The Cretaceous Bearpaw Shale is the most widespread formation; it crops out at the surface over most of the study area (fig. 4). The Cretaceous Judith River Formation crops out in the northeastern part of the study area; the Cretaceous Fox Hills and Hell Creek Formations and the Paleocene Fort Union Formation crop out locally in the southeastern part of the study area. Pleistocene glacial deposits and Quaternary alluvium, sand, and gravel are also widely distributed throughout the study area, where they typically are found in current and former river and stream valleys.

Pleistocene Glacial Deposits

Continental glaciers of Late Illinoian age (~190–127 ka) and Late Wisconsin age (~24–11 ka) (Davis and others, 2006) advanced from the north and northwest, damming and diverting the existing major drainages. This produced large glacial lakes, which then overtopped topographic divides and eroded new channels. Ground moraine, glaciofluvial deposits, and ice-margin features are common (Knechtel, 1959; Davis and others, 2006). Glaciers wrapped around the Bears Paw and Little Rocky Mountains, but did not entirely surround them. A large glacial lake, Lake Musselshell, formed south of the Laurentide ice sheet; the lake transported ice-rafted boulders and till that are now isolated occurrences in unglaciated areas (Davis and others, 2006). Large flat-floored valleys that are glacial meltwater channels are locally present. Younger postglacial drainages have reoccupied the preglacial courses in some areas. Larger areas of ice-rafted till have produced problems in delineating the maximum extent of glacial ice advance (for example, Gowan, 2013, and references therein).

Paleocene Sedimentary Rocks

The Fort Union Formation contains gray to greenish-gray smectitic shale and mudstone, and gray to yellow, very fine- to medium-grained sandstone. The unit locally contains coal beds. The formation is approximately 150 m thick in the study area, though elsewhere it ranges to 200 m thick (Wilde and Vuke, 2004a).

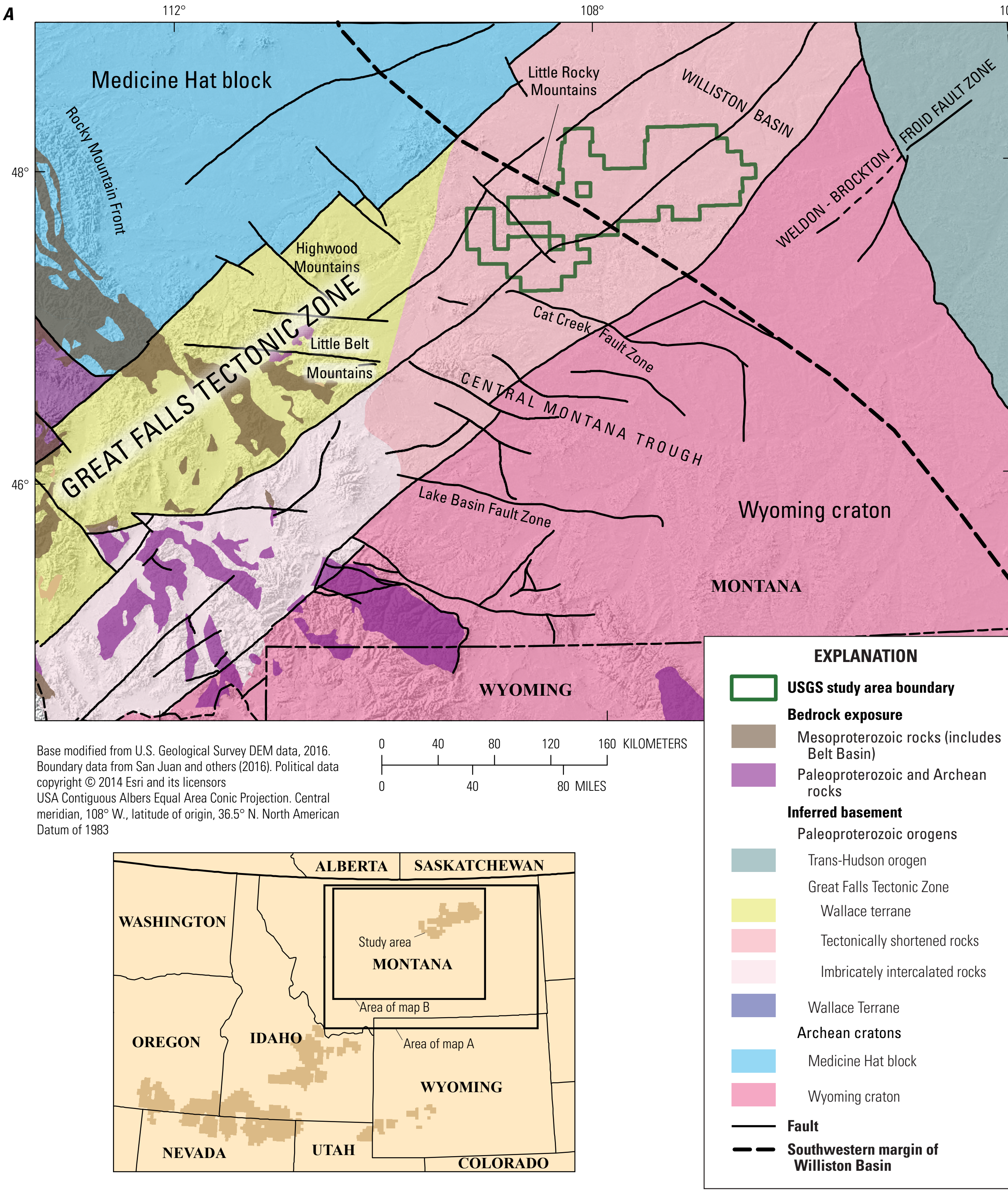
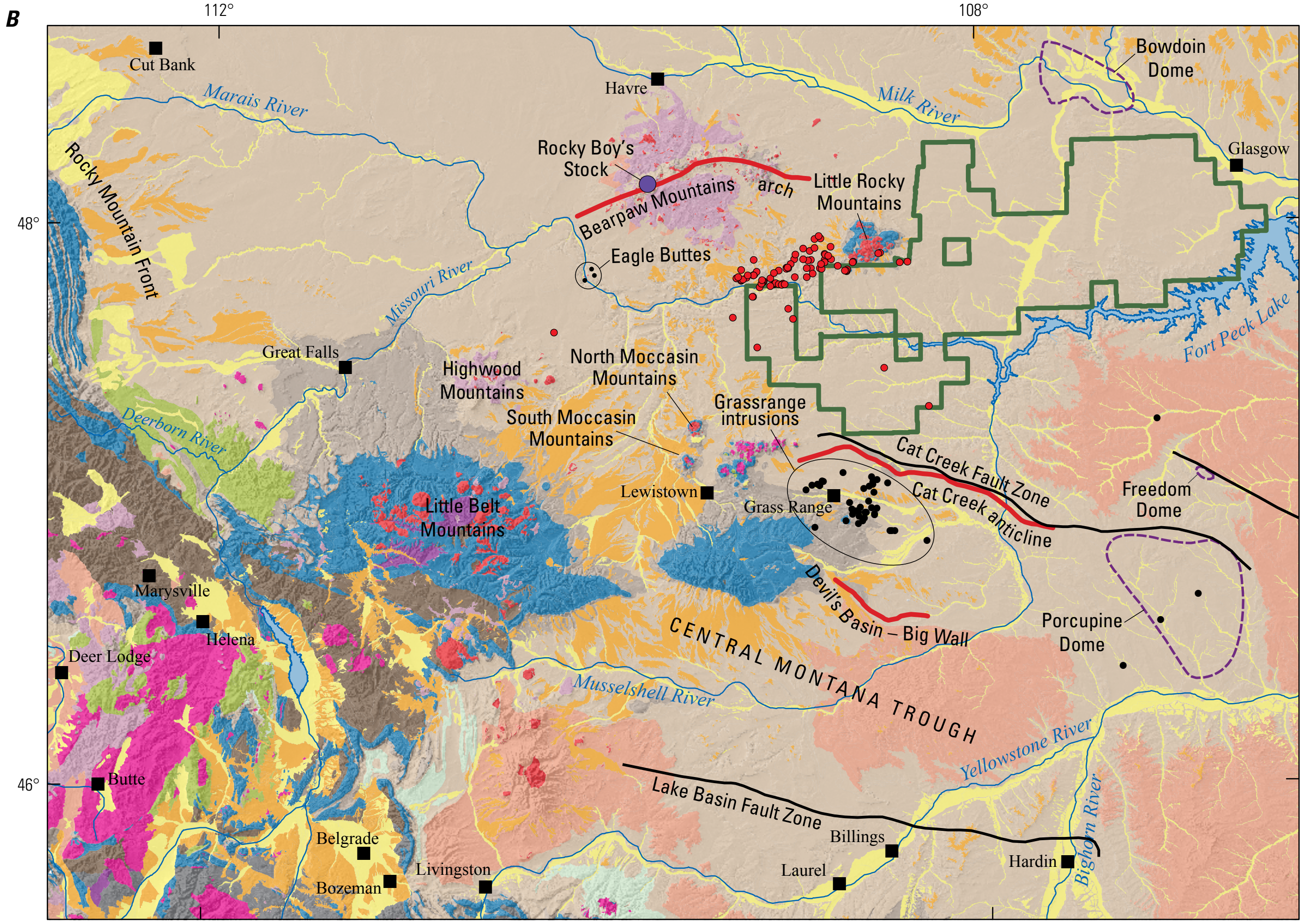


Figure 3. Maps showing tectonic and basement terrane setting (*A*) and geologic setting (*B,* facing page) of the North-Central Montana Sagebrush Focal Area (modified from Dobbin and Erdmann, 1955; St. John, 1999; Sims and others, 2004; Vuke and others, 2007; Woolley and Kjarsgaard, 2008; Garrity and Soller, 2009; Faure, 2010; U.S. Geological Survey, 2016b). USGS, U.S. Geological Survey.



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Political data

USA Contiguous Albers Equal Area Conic Projection. Central
meridian, 108° W., latitude of origin, 36.5° N. North American
Datum of 1983

EXPLANATION

- USGS study area boundary
- Domes
- Quaternary deposits
- Tertiary intrusive igneous rocks
- Tertiary volcanic igneous rocks
- Neogene sediments and sedimentary rocks
- Paleogene and undivided Tertiary sedimentary rocks
- Cretaceous to Tertiary intrusive igneous rocks
- Cretaceous to Tertiary volcanic igneous rocks
- Late Cretaceous igneous and sedimentary rocks
- Late Cretaceous sedimentary rocks
- Triassic to Early Cretaceous sedimentary rocks
- Paleozoic sedimentary rocks
- Mesoproterozoic metamorphic and sedimentary rocks and associated sills
- Paleoproterozoic rocks
- Archean rocks
- Fault
- Anticline
- Missouri River Breaks intrusions
- Other intrusive centers, diatremes, and dikes
- Rocky Boy's Stock

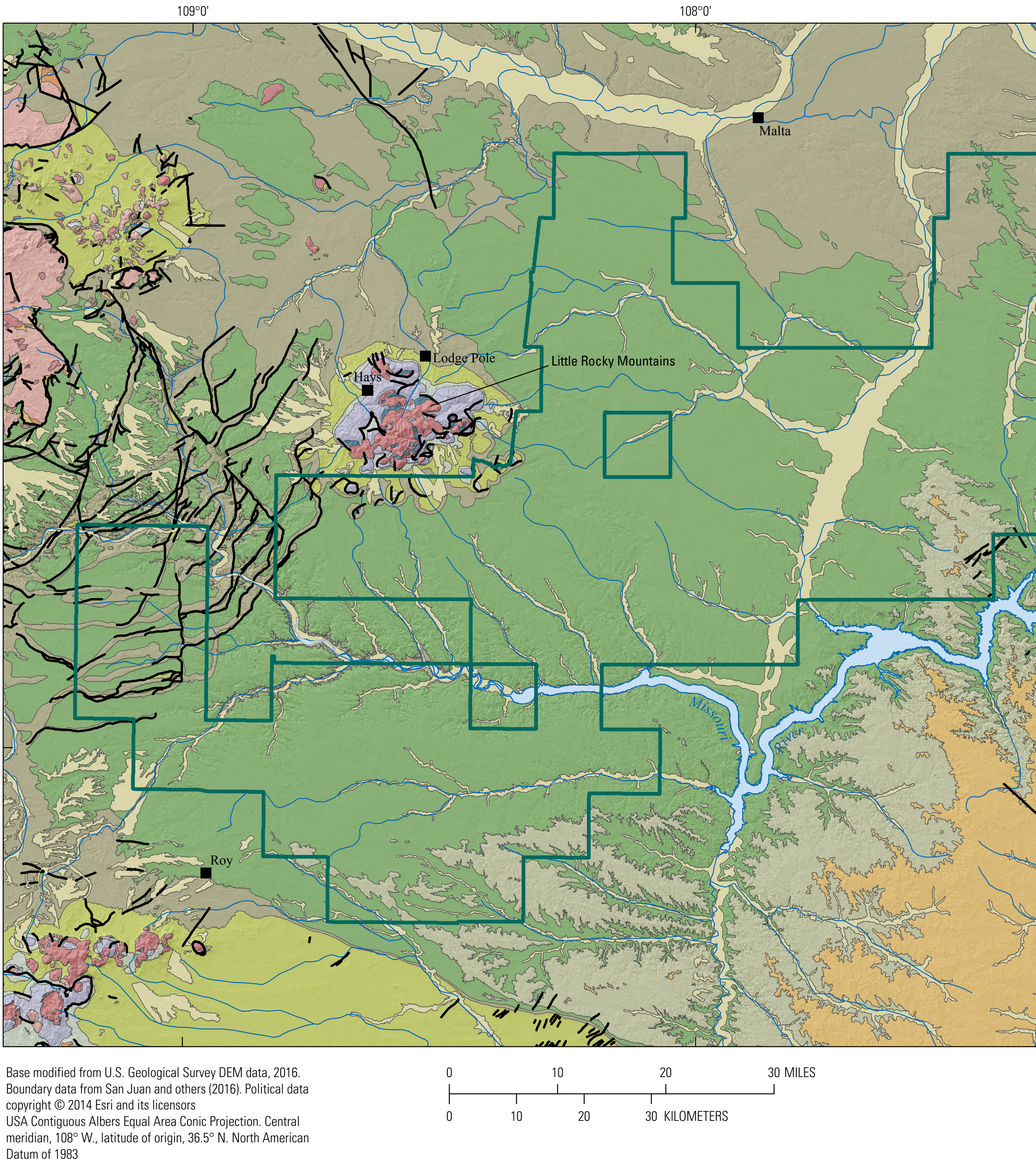
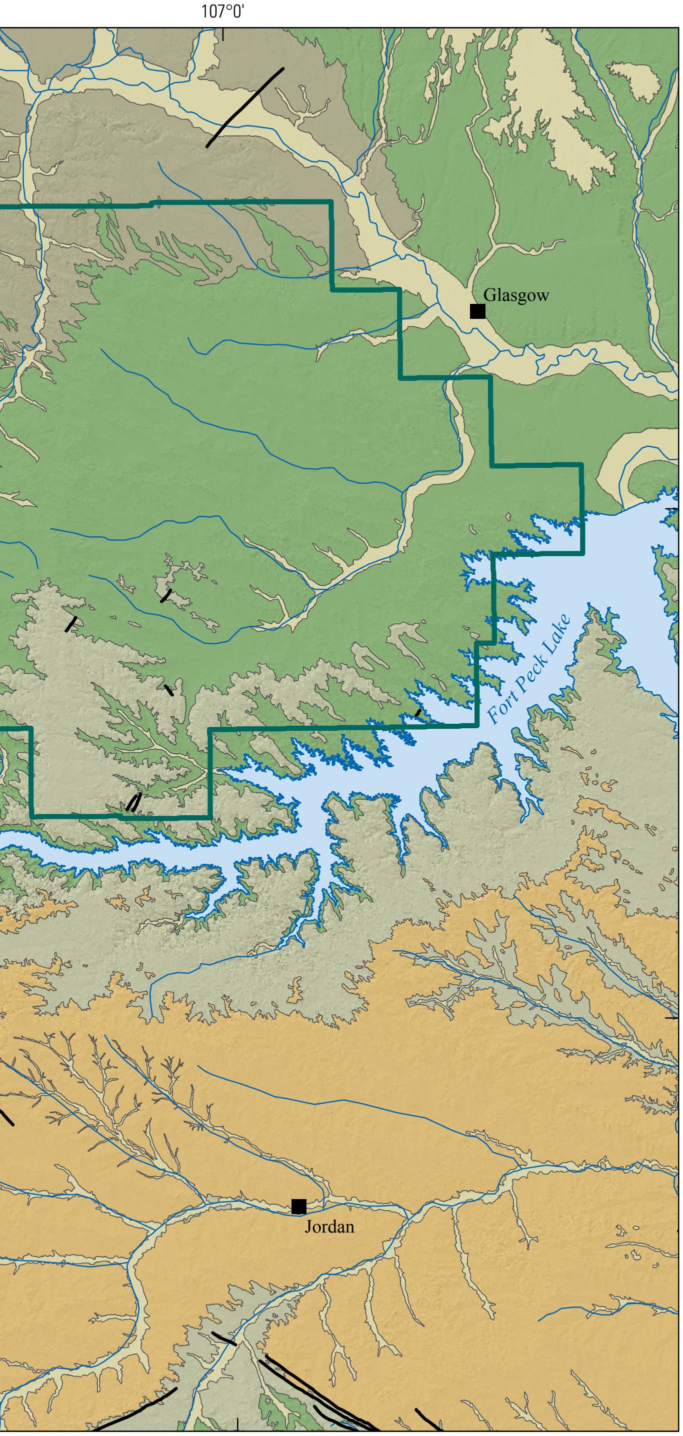
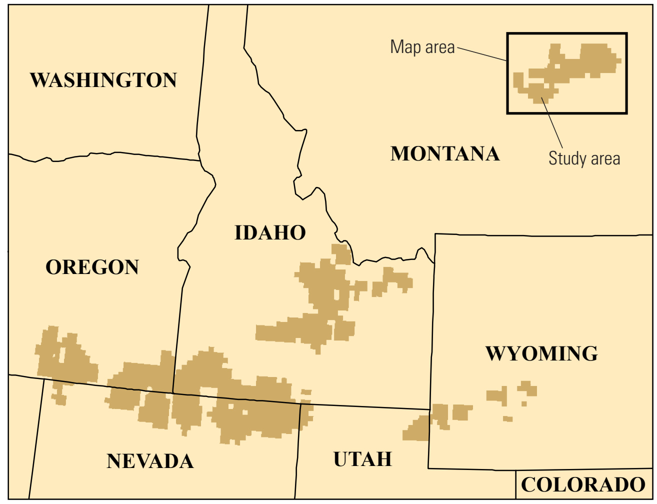


Figure 4. Map showing geology of the North-Central Montana Sagebrush Focal Area (modified from Vuke and others, 2007). The gravity-slide structures referred to in the text are the array of faults to the west and southwest of the Little Rocky Mountains. USGS, U.S. Geological Survey.





EXPLANATION

- USGS study area boundary
- Surficial deposits
- Eocene and younger sedimentary rocks
- Tertiary plutonic igneous rocks
- Tertiary volcanic igneous rocks
- Paleocene Fort Union Formation
- Upper Cretaceous
  - Hell Creek and Fox Hills Formations
  - Bearpaw Shale
  - Judith River Formation and Claggett Shale
- Lower to Upper Cretaceous Fall River and Eagle Sandstones
- Upper Jurassic to Lower Cretaceous sedimentary rocks
- Triassic and older sedimentary rocks
- Precambrian metamorphic rocks
- Fault

Cretaceous Sedimentary Rocks

Cretaceous rocks form the bedrock throughout the majority of the study area, and are also volumetrically important in the subsurface. These include, from youngest to oldest, the Hell Creek Formation, Fox Hills Formation, Bearpaw Shale, Judith River Formation, Claggett Shale, Eagle Sandstone, Telegraph Creek Formation, Niobrara Formation, Carlile Shale, Greenhorn Formation, Belle Fourche Shale, Mowry Shale, Thermopolis Shale, Fall River Sandstone, and Kootenai Formation (fig. 5, however, the Hell Creek and Fox Hills Formations are not shown).

The Hell Creek Formation is predominantly gray to light-brown sandstone, silty shale, and mudstone; it locally contains thin, lenticular coal beds or carbonaceous shale. The sandstone is fine to medium grained, and calcium-carbonate cemented concretions are typical in the fine-grained sandstone. The Hell Creek Formation is Late Cretaceous in the study area, though elsewhere it ranges to Paleocene in age, and locally it contains the osmium- and iridium-rich Chicxulub impact claystone (Moore and others, 2014). The contact with the underlying Fox Hills Formation may be either gradational or erosional. The average thickness in the study area is approximately 90 m (Johnson and Smith, 1964; Bergantino, 1999; Wilde and Vuke, 2004a).

The Upper Cretaceous Fox Hills Formation is light-brown to light-gray, thin- to thick-bedded, micaceous, fine- to medium-grained sandstone with ferruginous concretions in the upper part and thin-bedded siltstone and silty shale in the lower part. The average thickness in the study area is approximately 30 m (Knechtel, 1959; Porter and Wilde, 1993; Wilde and Vuke, 2004b).

The Bearpaw Shale is a medium- to dark-gray, fissile shale and mudstone that underlies low, sage-covered, gently rolling topography across most of the study area; it also forms the high bluffs and broken topography known as the “Missouri Breaks” along the Missouri River. Thin white bentonite layers are common throughout the Bearpaw, and in places these are thick enough to form the bentonite deposits that are described elsewhere in this report. Swelling clay minerals may locally produce “popcorn” weathering. Calcareous concretions are common in the unit, and in places they form mappable marker horizons. In most places in the study area, the top of the Bearpaw Shale has been eroded, but the average thickness of the entire unit in the region is approximately 350 m (Knechtel, 1959; Bergantino, 1999; Wilde and Vuke, 2004b).

The Judith River Formation is made up of light-colored interbedded sandstone, siltstone, sandy mudstone, claystone, and shale that record deposition in marine and terrestrial environments. The unit thickens westward in the study area, and ranges from 15 to 180 m thick (Knechtel, 1959; Rice, 1979; Porter and Wilde, 2001). Recent work in the western part of the study area has provided new insights into the stratigraphy and sedimentology of the Judith River Formation and has established the age of the contact between the Judith River Formation and Bearpaw Shale at approximately 75.2 Ma, based on $^{40}Ar/^{39}Ar$ dates of a bentonite unit at the base of the Bearpaw Shale (Rogers and others, 2016).

The Claggett Shale is dark-gray, thinly bedded shale with calcareous concretions, numerous bentonite beds and some thin, lenticular, siltstone and fine-grained sandstone beds. The Ardmore Bentonite Bed, which is a 9- to 12-m-thick zone of bentonite beds, occurs near the base of the formation and is a regionally significant marker horizon. The Claggett Shale thins eastward in the study area, but it is on average approximately 130 m thick (Alverson, 1965; Wilde and Vuke, 2004b).

The Eagle Sandstone contains two units in the study area. The upper unit contains light-gray sandy shale, siltstone, and thin sandstone beds. The lower unit contains a cross-stratified, fine-grained, light-yellow to buff-weathering sandstone unit that is mapped elsewhere as the Virgelle Sandstone. The total thickness of the Eagle Sandstone in the study area ranges from 60 to 90 m (Rice, 1976; Porter and Wilde, 2001; Wilde and Vuke, 2004b).

The Telegraph Creek Formation consists of light-gray to yellowish-gray sandy shale, siltstone, and thin-bedded sandstone with ironstone concretions in its lower part. The unit is approximately 50 m thick (Johnson and Smith, 1964; Wilde and Vuke, 2004b).

The Niobrara Formation contains calcareous and noncalcareous gray to dark-gray shale, siltstone, thin bentonite beds, and gray to brown calcareous or ferruginous concretions. The middle part of the formation contains the MacGowan Concretionary Bed, which is grayish-brown concretionary dolostone and limestone with phosphatic pellets and gray to black chert pebbles. The overall thickness in the study area is poorly constrained, but it may range to 100 m (Wilde and Vuke, 2004b; Vuke and others, 2007). This marine formation has a rich collection of vertebrate and invertebrate fossils, which provide well-defined biostratigraphic zones. Recent geochronology, using paired U-Pb analyses of zircon and $^{40}Ar/^{39}Ar$ analyses of sanidine from ash beds, has provided refined ages of 89.75 ± 0.38 Ma for the Turonian-Coniacian boundary, 86.49 ± 0.44 Ma for the Coniacian-Santonian boundary, and 84.19 ± 0.38 Ma for the Santonian-Campanian boundary (Sageman and others, 2014).

The Carlile Shale is a marine, dark-gray, noncalcareous, sandy shale. The upper two-thirds of the formation contain abundant calcareous concretions. The overall thickness in the study area is approximately 90 m (Wilde and Vuke, 2004b; Vuke and others, 2007).

The Greenhorn Formation is marine, gray to light-gray calcareous shale and shaly marl with local thin beds of limestone that range from 13 to 65 m thick in the study area (Rice, 1979; Wilde and Vuke, 2004b; Vuke and others, 2007).

The Belle Fourche Shale is a medium-gray to black marine shale that is up to 90 m thick in the study area. It contains ironstone concretions and numerous bentonite beds (Rice, 1979; Vuke and others, 2007).

The Mowry Shale is light-gray to dark-gray siliceous shale and subordinate thin-bedded, gray siltstone or very fine-grained sandstone. Bentonite is common in the formation, and

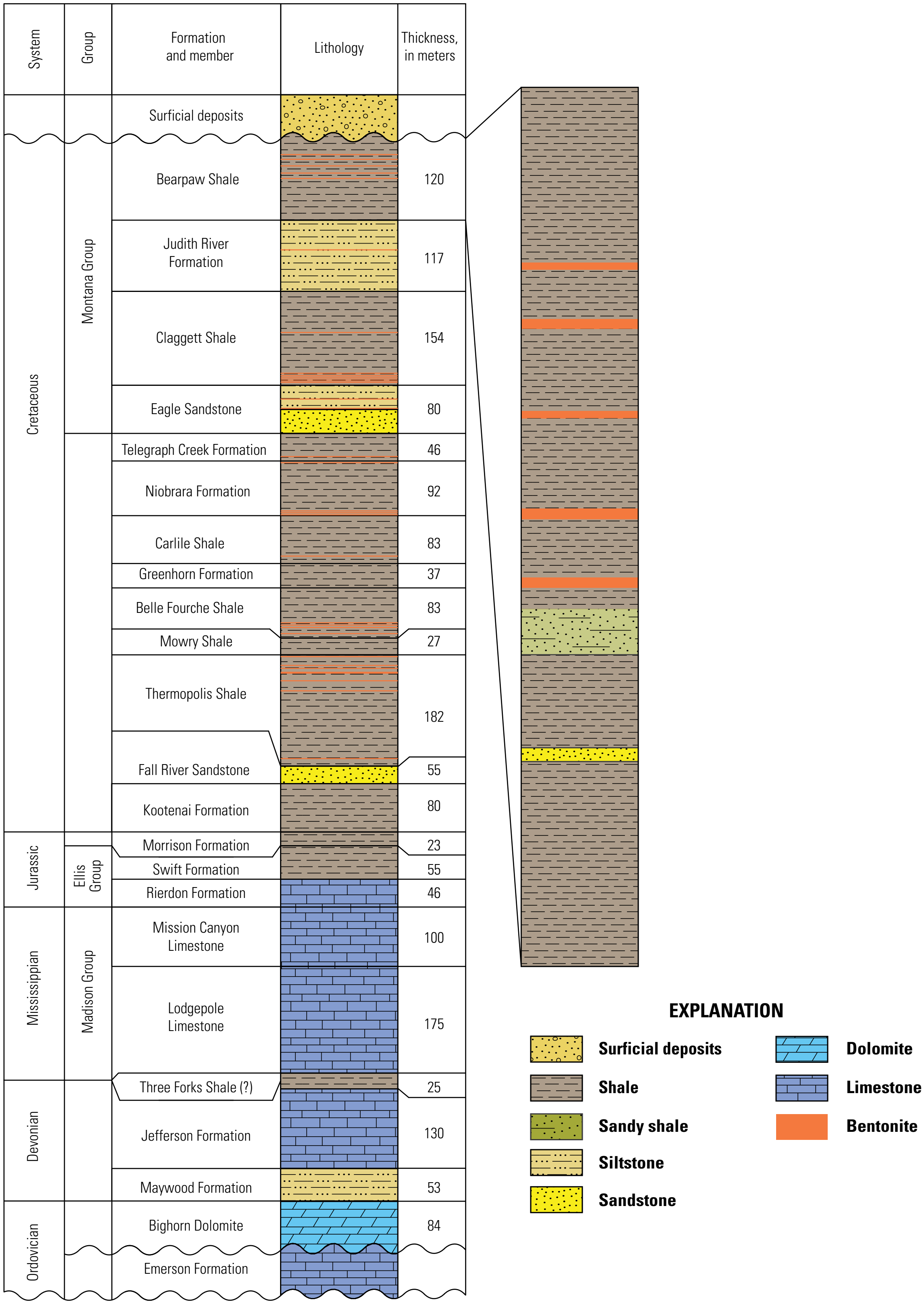


Figure 5. Lithostratigraphic column for the North-Central Montana Sagebrush Focal Area, showing stratigraphy exposed in Continental Oil Company's South Zortman well 1 (dry hole SZ-1), Phillips County, Montana (modified from Knechtel, 1959).

the Clay Spur Bentonite Bed is a widespread marker bed. The Mowry Shale is marine in origin, and it ranges from 30 to 140 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Thermopolis Shale is dark-gray to black marine shale with subordinate siltstone beds. The unit contains many thin bentonite beds and also many small ferruginous concretions. It ranges from 70 to 180 m thick in the study area (Knechtel, 1959; Vuke and others, 2007).

The Fall River Sandstone is light-gray to brown, fine- to medium-grained, quartzose sandstone with thin interbeds of dark-gray shale and siltstone. The unit was deposited in a nearshore marine environment, and it ranges from 11 to 30 m thick in the study area (Rice, 1979; Vuke and others, 2007).

The Kootenai Formation has a basal sandstone member that is commonly conglomeratic, and rests unconformably on the underlying Morrison Formation. The upper member is mottled, light- to dark-gray siltstone and shale with interstratified sandstone. The Kootenai ranges from 60 to 160 m thick in the study area (Knechtel, 1959; Rice, 1979).

Jurassic Sedimentary Rocks

Jurassic sedimentary rocks in the study area include the Morrison, Swift, and Rierdon Formations. These units contain an important lithostratigraphic change from younger shale and sandstone to older limestone; this transition marks a change from a marine shelf environment, where the limestone formed, to a younger terrestrial to shallow-marine environment, where the sandstone and shale formed.

The Morrison Formation is light-gray mudstone with subordinate sandstone and siltstone beds, and thin beds of coal. It ranges from 10 to 60 m thick in the study area, and it was deposited in lacustrine and fluvial environments (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Swift Formation has a light- to dark-gray shale basal member that is overlain by an upper member containing light-gray to greenish-gray glauconitic, flaggy-bedded, commonly fossiliferous, fine-grained sandstone with subordinate dark gray shale interbeds. The unit is 30 to 120 m thick, and it was deposited in a shallow marine environment.

The contact between the Swift Formation and the underlying Rierdon Formation marks an important transition from predominantly shaly siliciclastic units above to predominantly limestone and dolomite units below (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Rierdon Formation is light- to dark-gray, locally fossiliferous limestone. The lowermost part of the unit consists of greenish gray calcareous shale. The Rierdon Formation was deposited in lagoonal and marine-shelf environments, and it ranges from 30 to 60 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

Mississippian Sedimentary Rocks

The Mission Canyon Limestone is gray, relatively pure, massive to locally crossbedded limestone with chert beds and nodules, and solution cavities. The unit formed in a shallow marine environment, and it ranges from 120 to 220 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Lodgepole Limestone is dark- to light-gray, predominantly thin-bedded to massive limestone that typically contains chert lenses and interstratified shale partings. The unit formed in a shallow marine environment, and it ranges from 160 to 200 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

Devonian Sedimentary Rocks

The Three Forks Shale contains light-gray to light-green dolomitic to calcareous shale and siltstone that is locally sandy. The unit formed in marine to restricted-marine environments, and it ranges from 20 to 30 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Jefferson Formation has the 10- to 20-m-thick Birdbear Member in its upper part. The Birdbear is light- to medium-gray, sucrosic dolomite. The lower part of the Jefferson Formation, which forms approximately 90 percent of the unit, consists of dark-gray to brownish-gray finely crystalline limestone. The Jefferson Formation formed in a marine environment, and it ranges to 200 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Maywood Formation is gray to green to red to yellow to brown thin-bedded dolomitic limestone and dolomite that are interstratified with calcareous shale. This unit was deposited in a shallow marine environment, and it is approximately 40 to 50 m thick in the study area (Knechtel, 1959; Vuke and others, 2007).

Ordovician Sedimentary Rocks

The Bighorn Dolomite is dappled-gray to very pale orange crystalline dolomitic limestone that locally contains sandstone near its base. The unit formed in a marine shelf environment, and it ranges from 20 to 80 m thick in the study area (Knechtel, 1959; Rice, 1979; Vuke and others, 2007).

The Emerson Formation is dark-gray to green shale with upward-increasing interbeds of light-gray to white glauconitic sandstone, sandy and glauconitic marlstone, and fossiliferous limestone. It ranges from 290 to 340 m thick in the study area (Knechtel, 1959; Rice, 1979).

Cambrian Sedimentary Rocks

The Flathead Sandstone consists mainly of light-gray, green, and tan sandstone. It is partly argillaceous, and contains some interbedded fine-grained conglomerate. The thickness is approximately 15 m in the Little Rocky Mountains (Knechtel, 1959).

Precambrian Sedimentary Rocks

Exposed Precambrian rocks in the Little Rocky Mountains are metasedimentary and metavolcanic (Knechtel, 1959; Peterman, 1981). The metasedimentary rocks are felsic gneisses and schists that contain quartz, potassium feldspar, and plagioclase, with varying amounts of biotite, muscovite, chlorite, hornblende, garnet, and kyanite, and with accessory apatite, zircon, magnetite, and pyrite. The metavolcanic rocks are mafic hornblende-plagioclase and hornblende-plagioclase-garnet gneisses that are generally fine grained.

Leasable Minerals

Leasable minerals include leasable fluid and solid minerals (Mineral Leasing Act, as amended, February 1920; 43 CFR 3000–3599, 1990). 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 (appendix 1 in Day and others, 2016). Oil shale, native asphalt, sodium, potassium, and sulfur do not occur within or near the study area, so they are not considered further. This section describes potash, coal, geothermal, oil and gas, and phosphate occurrences.

Potash

No significant potash salt occurrences are known within the North-Central Montana Sagebrush study area. The nearest potash resources are more than 100 km to the northeast in Paleozoic strata near the western margin of the Williston Basin (fig. 6; Anderson and Swinehart, 1979; Kruger, 2014). A potash tract referred to as the Belle Plaine was identified by Orris and others (2014) in the northwestern part of North Dakota and the northeastern part of Montana that coincide with the Williston Basin.

The Williston Basin potash deposits are an extension of large potash deposits that are mined extensively in the Elk Point Basin in Saskatchewan Province, Canada (fig. 6). Potash resources in the Williston Basin are possibly the largest known, but largely unexploited potash resources in the United States and are in the Devonian Prairie Formation of the Elk Point Group (Kruger, 2014). The great depth (>3 km) of the Prairie Formation within parts of the Williston Basin would limit potash recovery to in place solution mining. The Williston Basin potash deposits are of the marine, stratabound type that formed during retreat and evaporation of a Devonian seaway (Peterson and MacCary, 1987). These types of deposits, which formed during evaporation of Paleozoic intracontinental seaways, tend to be the largest sources of potash mined today. In comparison, the Quaternary, closed-basin brine potash sources, such as those that are associated with the Pleistocene Lake Bonneville and Holocene Great Salt Lake in Utah (Warren, 2010), are much smaller.

Coal

The USGS has not conducted a formal quantitative coal resource assessment for the North-Central Montana Sagebrush study area. However, a series of four USGS Leasable Mineral and Waterpower Land Classifications maps indicated large areas of coal-bearing formations surrounding and somewhat overlapping the study area (Bateman and Lutz, 1976; Bateman and Allen, 1977, 1978; Bateman and others, 1977). The more recent “Coal fields in the conterminous United States” (East, 2013) more precisely defined the coal-bearing areas. The report shows that the westernmost part of the study area falls within the North-Central coal region (fig 7). Four additional coal-bearing areas are outside of the study area but partially overlap the southwest, southeast, and east parts of the map area shown in figure 7: the Great Falls coal field, Garfield County coal field, Powder River coal region, and the Fort Union coal region, respectively. These areas contain coal of lignite to bituminous rank in Jurassic to Tertiary sedimentary rocks. As discussed below, the coal beds within the study area are not likely to generate economic interest in the future.

The coal beds in the North-Central coal region are Late Cretaceous in age, and are subbituminous in rank (Combo and others, 1949; Wilde, 2010). The coal beds in the North-Central coal region are restricted to two coal-bearing formations—the Judith River Formation and the Eagle Sandstone—that are separated stratigraphically by marine shales and thin sandstone beds of the Claggett Shale. Brief descriptions of the Judith River Formation and the Eagle Sandstone are provided by Vuke and others (2007). Both units have thin, laterally discontinuous coal beds that are interbedded with sandstones, sandy shales, and carbonaceous shale. In Montana, the Judith River Formation reaches a maximum thickness of approximately 300 m. Most of the coal in the Judith River Formation occurs in two thin discontinuous beds in the upper 20 m of the formation where the thickness of the two coal beds ranges from 0.8 to 2.0 m of impure coal containing bone coal partings; these coal beds have been mined for local ranch use, predominantly for home heating (U.S. Geological Survey and Montana Bureau of Mines, 1963).

In Montana, the Eagle Sandstone reaches a maximum thickness of approximately 150 m, and it contains thin, laterally discontinuous lenses of coal in a 25 m layer of carbonaceous shale in the upper part of the unit (Vuke and others, 2007). Owing to the thinness and poor quality of the coal, mining has been limited to that needed for local use. Coal beds in the Eagle Sandstone near the Bears Paw Mountains

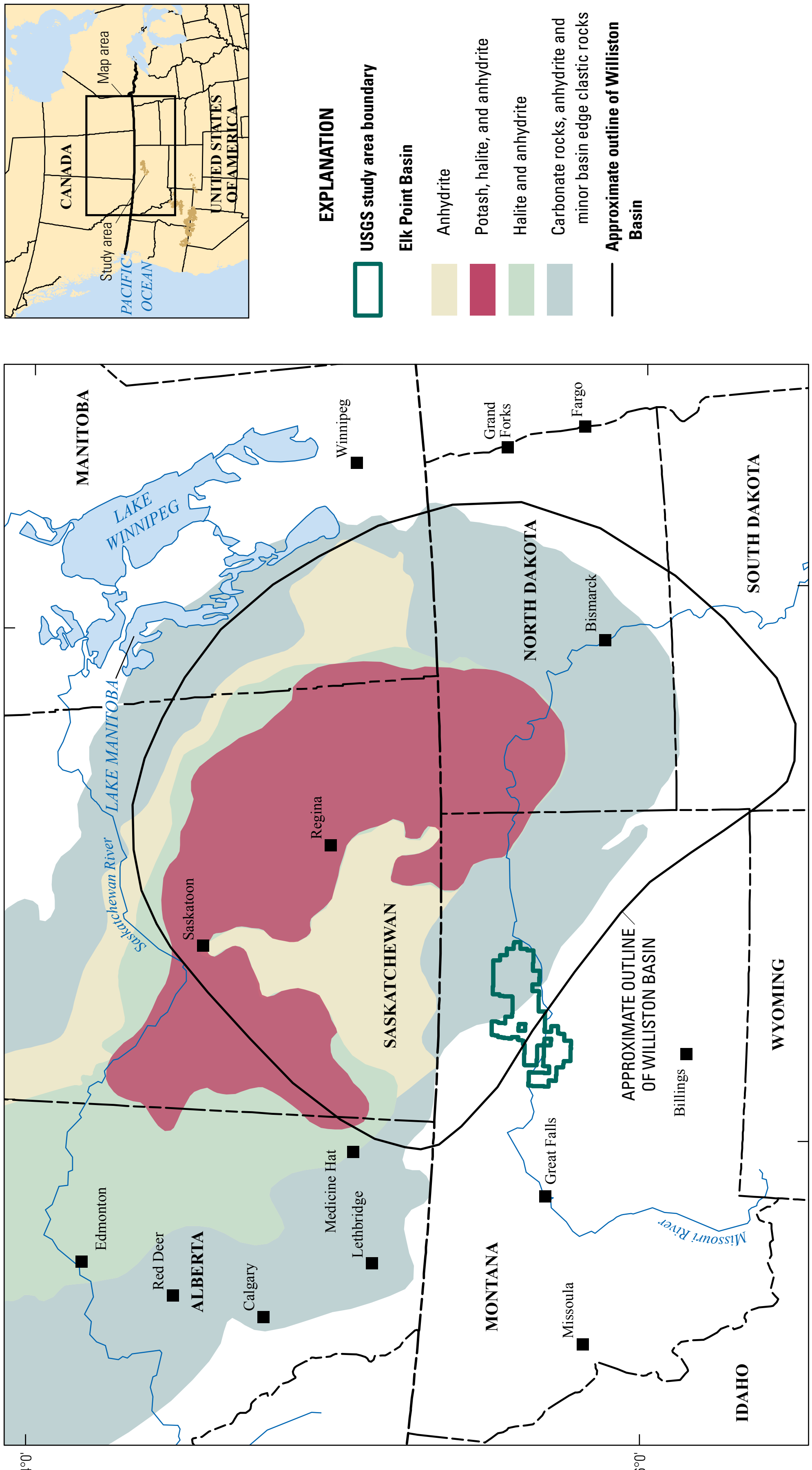


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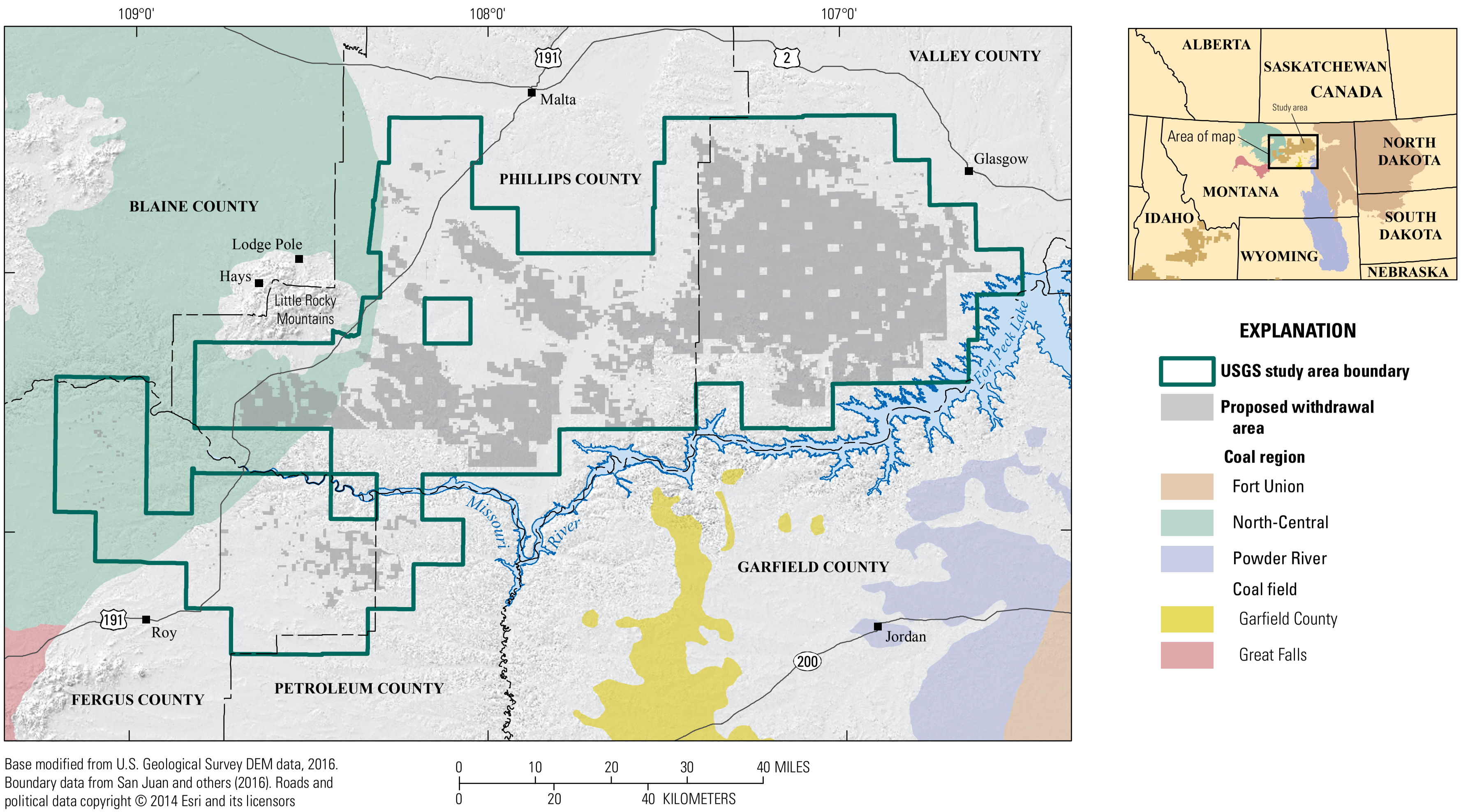
Figure 6. Map showing the approximate extent of the Williston Basin and evaporite and carbonate rocks of the Elk Point Basin (modified from Worsley and Fuzesy, 1979; St. John, 1999). USGS, U.S. Geological Survey.



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 7. Map of the North-Central Montana Sagebrush Focal Area showing areas with coal-bearing formations (from East, 2013). USGS, U.S. Geological Survey.

have not been mined since 1925 (U.S. Geological Survey and Montana Bureau of Mines, 1963).

The coal beds of the Judith River Formation and the Eagle Sandstone within the study area are exposed at the surface along a narrow zone where Cretaceous rocks are upturned along the margin of the uplift associated with the doming and emplacement of the syenite in the Little Rocky Mountains. Away from the Little Rocky Mountains uplift area, to the north, east, and south, the Judith River Formation and the Eagle Sandstone are relatively flat lying and underlie the Bearpaw Shale (commonly 350 m thick in the study area) and Quaternary alluvium deposits (fig. 5; Porter and Wilde, 2001; Vuke and others, 2007). Owing to the thinness, lack of lateral continuity, poor quality, and depth of cover, the coal beds in both the Judith River Formation and the Eagle Sandstone within the study area are not likely to generate economic interest in the future.

Geothermal

This section characterizes the nature and occurrence of low-temperature geothermal resources, the geothermal resource potential, or favorability, of moderate- to high-temperature hydrothermal systems, and the resource potential for enhanced geothermal systems (EGSs) within the North-Central Montana Sagebrush Focal Area. Enhanced geothermal systems are geothermal resources that possess the necessary heat, but lack sufficient permeability to generate electric power. In these systems, a geothermal reservoir is engineered (through hydraulic, chemical, or thermal stimulation) to create sufficient permeability to support fluid circulation that can effectively mine heat from the surrounding rock.

Geology and Occurrence

Inventories of geothermal occurrences in Montana (Reed and others, 1983; Lienau and Ross, 1996; Metesh, 2000) identify only one thermal spring, Landusky Plunge Springs, with a temperature of 24 °C, and four thermal water wells with temperatures ranging from 16 to 27 °C within the study area. There are several other warm springs and wells in and near the Little Rocky Mountains (fig. 8), but there are no known moderate- to high-temperature geothermal systems in the area. The nearest known moderate- to high-temperature geothermal system is more than 200 km to the west of the study area at Marysville, Montana. This relative 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 area (fig. 8). 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).

Exploration and Development

Exploration for geothermal systems within and near the study area have been limited to three crustal heat flow measurements approximately 100–150 km to the south and four measurements approximately 150–200 km to the west (Williams and DeAngelo, 2011; locations shown on figure J2 of Glen and others, 2016). The three measurements to the south range from 43 to 51 mW/m^2, with an average of 46 mW/m^2. The four measurements to the west are more variable, ranging from 67 to 100 mW/m^2, with an average of 77 mW/m^2. Based on these relatively distant observations alone, it is uncertain what the average value of crustal heat flow is for the region covered by the study area.

A compilation of bottom-hole temperature (BHT) records from oil and gas exploration wells and estimates of geothermal gradients within the associated sedimentary formations has been published by Gunderson (2011). For wells in the study area, BHTs range from 73 to 85 °C over a depth interval from 2,300 to 2,800 m (Gunderson, 2011). Although measured BHTs typically underestimate true formation temperatures, corrections to these data will be on the order of 10 to 15 °C hotter. These results are consistent with the observation from the sparse heat flow data that the study area is not characterized by high temperatures at shallow depths typically required for commercial geothermal operations. Implications for lower temperature geothermal applications are discussed below.

Results of Previous Assessments

A previous USGS geothermal resource assessment (Williams and others, 2008) did not locate any identified moderate- and high-temperature geothermal systems within the study area. The assessment for undiscovered resources was based in part on a series of 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, Reed, and others, 2009). Figure 8 illustrates the distribution of relative geothermal potential from these analyses across the region encompassing the study area. The low values are consistent with the absence of any identified moderate- and high-temperature geothermal systems.

Low-temperature geothermal resources of this region were assessed by Reed (1983), with inventories of low-temperature springs and wells published by Reed and others (1983), Lienau and Ross (1996), and Metesh (2000). As noted above, one thermal spring and four thermal wells are located within the study area (table 2). In addition, Reed (1983) considered the low-temperature potential associated with thermal aquifers in the deeper sedimentary units of the region. These aquifers could be exploited locally for direct use applications, and it is conceivable that under more favorable commercial conditions, geothermal power projects similar to the Rocky Mountain Oilfield Testing Center-Powder River Basin

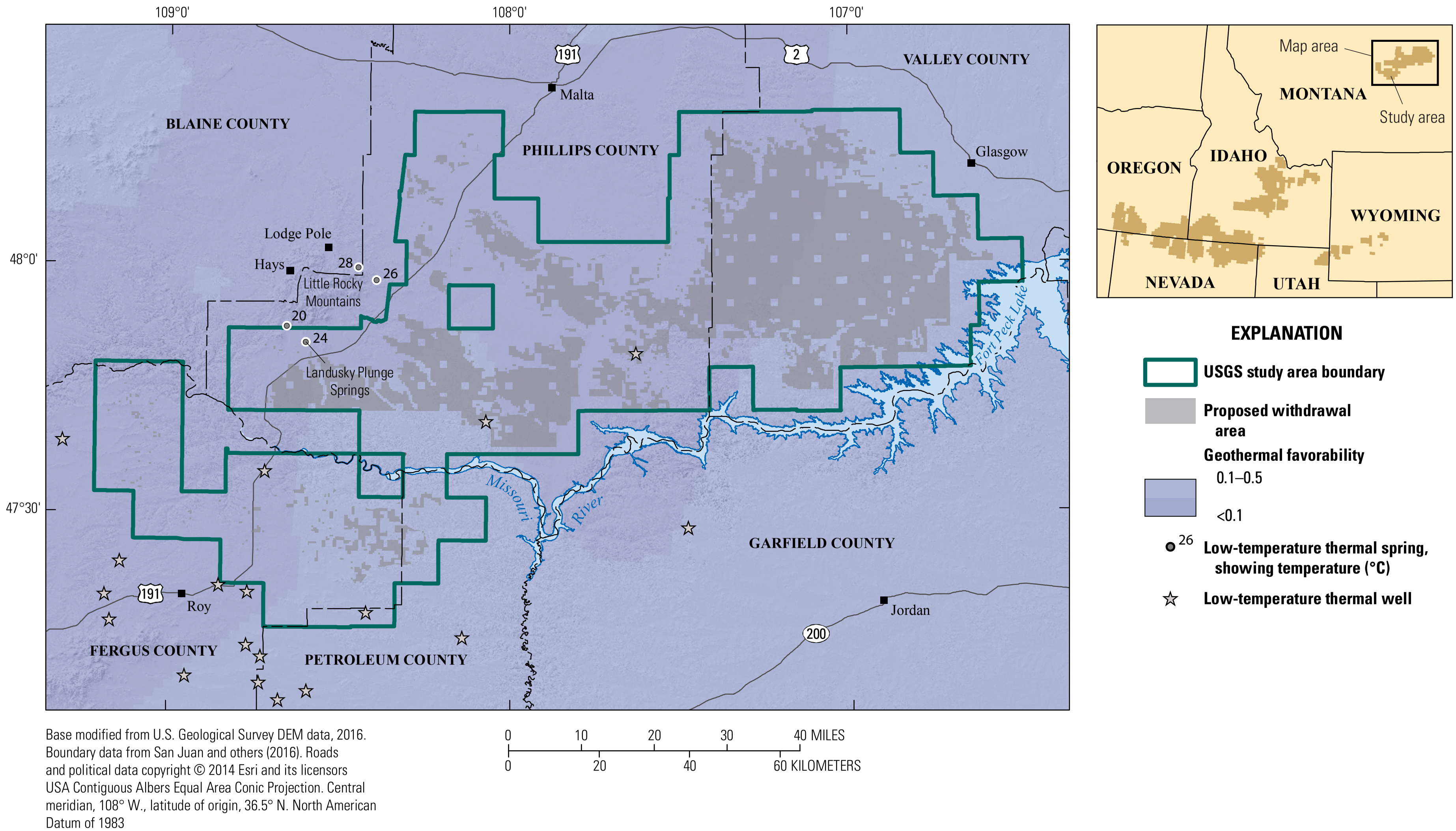


Figure 8. Map showing the location of thermal springs and wells, overlain on the logistic regression results for geothermal favorability for the North-Central Montana Sagebrush Focal Area (from Williams and others, 2008). Warm springs show temperatures in degrees Celsius. The units for geothermal favorability represent the ratio of posterior probability to prior probability for each cell as derived from a combination of logistic regression models for the occurrence of geothermal systems. The cool colors indicate low favorability for geothermal systems. USGS, U.S. Geological Survey.

Table 2. Occurrence of identified low-temperature geothermal systems in the North-Central Montana Focal Area.

[See figures 8 and 9 for a plot of the locations of identified geothermal systems. Data based on results from Williams and others (2008). Name is system name. Type is data type (well or spring). Sources: USGS, Reed and others (1983); Geo-Heat Center (GHC), Boyd (2002)]

Name/owner and location	Type	Source	Mean temperature (°C)	Latitude (decimal degrees)	Longitude (decimal degrees)
Landusky Plunge springs	Spring	USGS	24	47.843	-108.599
John Matovich; 23 mi SW Sun Prairie, Mont.	Well	GHC	16	47.683	-108.07
Merlin Busenbark; 1 mi S of Valentine, Mont.	Well	GHC	27	47.299	-108.421
Jim McCollum; 10 mi NW of Mathison Ranch, Mont.	Well	GHC	18.8	47.582	-108.718
Whitmayer Assoc.; 4.5 mi SE of Sun Prairie School, Mont.	Well	GHC	15.6	47.819	-107.629

demonstration project in Wyoming described by Anderson (2010) could be developed in Montana. However, no site-specific assessment has been conducted in the study area to identify permeable thermal aquifers that are associated with 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 cutoff 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 cutoff was not included in the assessment. The region covered by the study area falls at or just below that cutoff on a national-scale model of temperature at a depth of 6 km (fig. 9, table 3). Although an updated version of the model with refined spatial corrections for variations of thermal properties in sedimentary basins (as discussed by Williams and DeAngelo [2011]) moves the average into the range of 150 to 175 ºC, this region cannot be considered as having significant EGS resource potential.

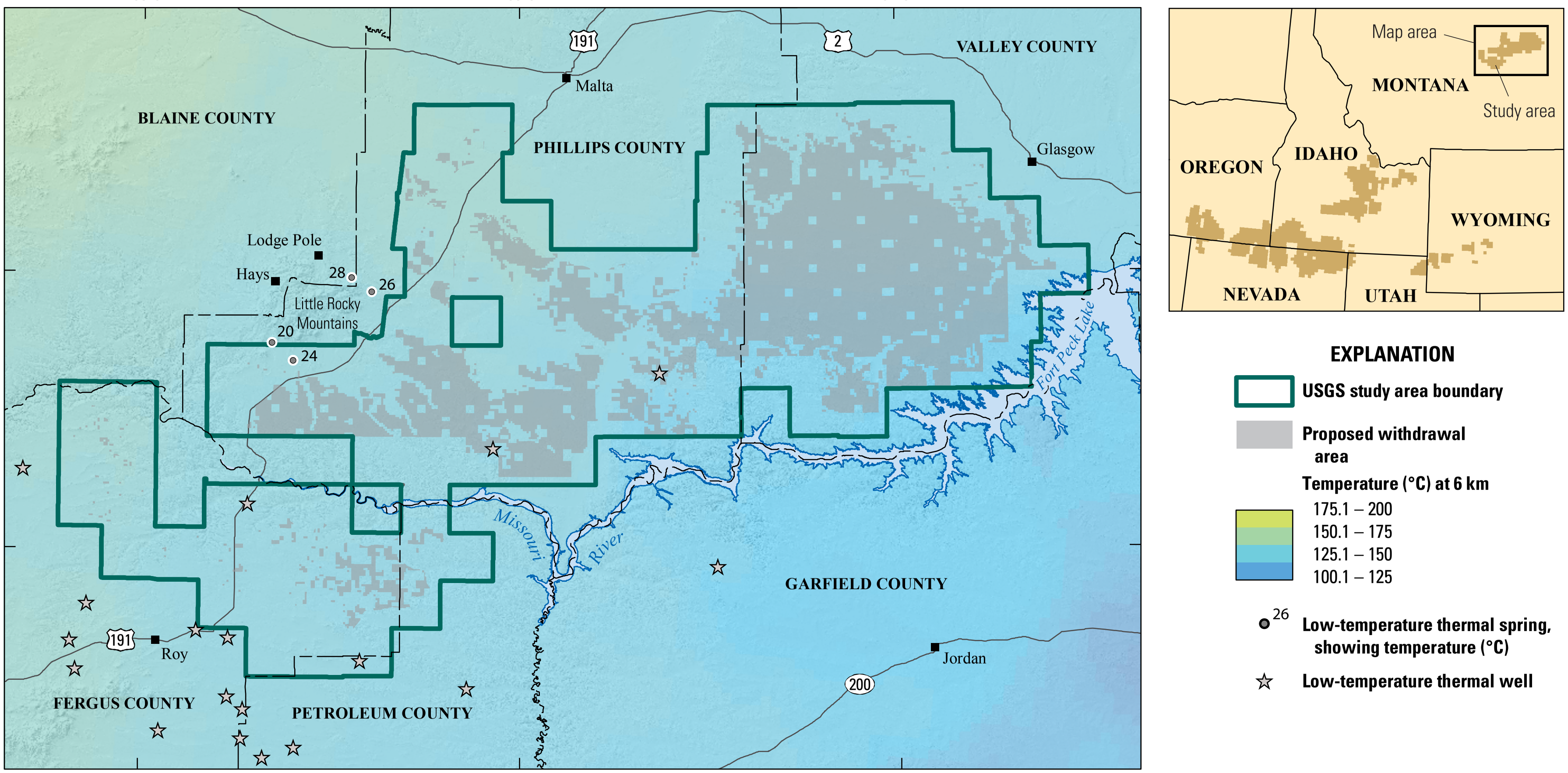
Oil and Gas

The North-Central Montana Sagebrush Study Area lies within the North-Central Montana and Williston Basin oil and gas provinces. According to IHS Enerdeq Well data (IHS Energy Group, 2016), there has been no significant oil or gas production within the study area. However, there has been gas produced adjacent to the study area in fields such as Leroy, Vandalia, Ashfield, Bowdoin, and Strater (fig. 10). Bowdoin field is the oldest, and it is just north of the study area. It was discovered in 1913, and it produces biogenic gas from Cretaceous reservoirs (Dyman, 1995).

The Central-Montana area has been extensively assessed for potential hydrocarbon resources. The Williston Basin Province, which overlaps the eastern side of the study area, was assessed in 1995, and five plays, which are known or postulated oil and gas accumulations, were defined in this area (Peterson and Schmoker, 1995). These plays include the (1) Madison (Mississippian), (2) Red River (Ordovician), (3) Middle and Upper Devonian (Pre-Bakken–Post-Prairie Salt), (4) Pre-Prairie Middle Devonian and Silurian, and (5) Post-Madison through Triassic Clastics. The estimated mean resources for these plays within the Williston Basin Province are 344 million barrels of oil (MMBO), 99.6 million barrels of natural gas liquids (MMBNGL), 374.3 billion cubic feet of associated-dissolved gas (BCFG), and 500.2 BCFG of non-associated gas (Peterson and Schmoker, 1995). Although none of these plays lie directly on the study area, they are mentioned owing to their proximity to the study area.

Oil and gas assessments were also conducted by the USGS in 1995 in the North Central-Montana Province, which overlies the majority of the study area (fig. 10). In 1995, the cumulative conventional production in the province was more than 440 million MMBO and 1.1 trillion cubic feet of gas, and it included the following plays (Dyman, 1995) within the sagebrush study area: (1) Cambrian-Ordovician Sandstones, (2) Red River Carbonates, (3) Bakken Shale Fracture Systems, (4) Devonian-Mississippian Carbonates, (5) Tyler Sandstone, (6) Fractured-Faulted Carbonates in Anticlines, (7) Jurassic-Cretaceous Sandstones, (8) Shallow Cretaceous Biogenic Gas, (9) Northern Great Plains Biogenic Gas Play with "Moderate Potential" (Suffield Block Analog), and (10) Northern Great Plains Biogenic Gas Play with "Low Potential". The assessed undiscovered mean resources for these plays are 270 MMBO, 840 BCFG, and 10 MMBNGL (Dyman, 1995).

In 2000, the USGS assessed the undiscovered biogenic (microbial) continuous gas resource potential in the North-Central Montana Province and estimated a mean of 6,192 billion cubic feet of shallow gas (U.S. Geological Survey North-Central Montana Province Assessment Team, 2008). This large area includes most of central and eastern Montana. Within this assessment, there are seven different assessment



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USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 9. Map showing the locations of low-temperature thermal springs and wells overlain on the estimated temperature at 6 km depth, for the North-Central Montana Sagebrush Focal Area (modified from Metesh, 2000; Williams and DeAngelo, 2011). Warm springs show temperatures in degrees Celsius. USGS, U.S. Geological Survey.

Table 3. Statistics of geothermal favorability and temperature at 6-km depth for the North-Central Montana Focal Area, and for the entire Western United States.

[Geothermal favorability based on logistic regression analysis results of the 2008 USGS national geothermal assessment (Williams and others, 2008). Temperature at 6 km determined from Williams and DeAngelo (2011). NCI, North-Central Montana Focal Area; WUS, Western United States]

Area	Mean value of favorability	Minimum value of favorability	Maximum value of favorability	Standard deviation of favorability	Mean temperature at 6 km depth (°C)	Minimum temperature at 6 km depth (°C)	Maximum temperature at 6 km depth (°C)	Standard deviation of temperature at 6 km depth (°C)
NCI	0.13789559	0.05211746	0.25275114	0.0810685	148.7	138.7	158.2	4.2
WUS	1.21126121	0.01127062	58.6081276	2.04851707	181.7	86.2	290.2	34.5

units (AUs) including the (1) Judith River Formation, (2) Eagle Sandstone and Claggett Shale East, (3) Eagle Sandstone and Claggett Shale West, (4) Niobrara-Carlile, (5) Greenhorn-Lower Belle Fourche, (6) Greenhorn-Upper Belle Fourche, and (7) Bowdoin Dome AUs. The Judith River Formation AU was estimated to contain the most undiscovered biogenic gas resource with a mean of 1,855 BCFG (U.S. Geological Survey North-Central Montana Province Assessment Team, 2008).

The USGS also assessed conventional resources in the area and within the Williston Basin Province in 2010. Some of the these AUs overlap the North Central-Montana study area and include the (1) Mission Canyon-Charles, (2) Lodgepole, (3) Red River Fairway, (4) Interlake-Stonewall-Stony Mountain, and (5) Winnipeg-Deadwood AUs (see chapters 3 and 4 of U.S. Geological Survey Williston Basin Province Assessment Team, 2011). The assessed undiscovered mean resources for these AUs are 112 MMBO, 451 BCFG, and 50 MMBNGL. The study area only covers a small part of these AUs (U.S. Geological Survey Williston Basin Province Assessment Team, 2011).

All of the 115 PLSS townships that contain proposed withdrawal areas are associated with at least one play or AU (appendix 3). Although there are many potential resources in the area, there has not been any significant hydrocarbon production within the study area; the overall potential appears to be low. For more details about the oil and gas resource assessment of this area, please see the aforementioned USGS oil and gas assessment reports (Dyman, 1995; Peterson and Schmoker, 1995; U.S. Geological Survey North-Central Montana Province Assessment Team, 2008; U.S. Geological Survey Williston Basin Province Assessment Team, 2011).

Phosphate

Phosphate is classified by BLM as a non-energy solid leasable mineral and is leased under the Mineral Leasing Act of 1920, as amended, and is not directly related to energy production. Phosphate is administered by BLM pursuant to 43 CFR 3500—“Leasing of solid minerals other than coal and oil shale” regulations.

Phosphorus is an essential element for plant and animal nutrition, and it is indispensable for world food production (Van Vuuren and others, 2010; Ashley and others, 2011). It is mined from phosphate rock that is converted to phosphoric acid, which is the basis of many fertilizer and non-fertilizer products (Cordell and White, 2014).

Sedimentary phosphate deposits (phosphorites) form in marine shelf-slope or epeiric settings along the margins of continents in middle to low latitudes where nutrient-rich, O_2-depleted bottom waters are upwelled from depths of 100 to 600 m and delivered to the photic zone, promoting primary productivity that concentrates phosphate in the remains of organisms at all levels of the food web. The phosphate is released through respiration of biogenic debris as it settles through the water column. In settings of low siliciclastic detrital input and low carbonate production, and in suboxic to reducing to denitrifying conditions that may include iron redox cycling at or beneath the bottom water-substrate interface, microbially mitigated early diagenetic authigenic phosphate mineralization occurs as crusts, hardgrounds, laminae, nodules, or pellets within the organic-rich sediments (Glenn and others, 1994; Föllmi, 1996; Moyle and Piper, 2004; Piper and Perkins, 2004; Filippelli, 2011). Subsequent to burial and exhumation, phosphate-enriched grains and fragments are commonly hydraulically and biologically reworked, concentrated, and re-deposited to form granular phosphorites (Glenn and others, 1994). Such reworking at sustained intervals of widespread erosion commonly results in nodular lag deposits at the base of unconformable sedimentary units (Glenn and others, 1994; Filippelli, 2011).

Major phosphorite deposits in the United States are related to zones of oceanic upwelling that took place (1) along the western margin of North America during the Permian, which formed the western phosphate field in Wyoming, Idaho, Montana, and Utah and (2) off the southeastern North American coast in the Miocene, which formed phosphate deposits in Florida and the Carolinas (Sheldon, 1981; Zientek and Orris, 2005; Filippelli, 2011).

The study area lacks Permian units such as the Phosphoria Formation, which are important sources of phosphorite in southeastern Idaho and adjoining States (Piper and Perkins, 2014). Instead, phosphate is confined to part of the Niobrara Formation, where it occurs in a concretionary dolostone and limestone bed that contains phosphatic pellets and gray to black chert pebbles, or as a phosphatic pebble bed that is as much as 10 cm thick (Cobban and others, 1976; Vuke and others, 2007). These thin and minor occurrences are insignificant compared to the phosphorite deposits that are mined elsewhere in the United States, such as the Permian Phosphoria Formation or Miocene deposits of Florida, and consequently the study area lacks rocks that may be prospective for phosphate deposits.

There is no known exploration or mining activity for phosphate in the north-central Montana study area. There are no known USGS assessments for phosphate in the north-central Montana study area.

Locatable Minerals

The BLM defines locatable minerals as those minerals not leasable under the Mineral Leasing Acts and not salable under the Mineral Materials Act of 1947 (43 CFR 3830.11). Generally this includes valuable deposits of metallic minerals and industrial minerals (appendix 2 in Day and others, 2016).

Based on the geology of the study area, records of past production and current exploration, and consideration of geochemical, geophysical, and remote sensing data, four commodities need to be assessed as locatable minerals in the study area: gold, silver, bentonite, and diamond. The other locatable minerals listed in appendix 2 of Day and others (2016) have no production records in the study area, and the study area lacks the necessary geologic settings to host the mineral deposit types where these minerals occur (appendix 3 in Day and others, 2016). Therefore, these other locatable minerals are not considered further.

Mineral Systems and Mineral Deposit Types

The four commodities, bentonite, diamond, gold, and silver, that need to be assessed as locatable minerals in the study area occur in different mineral systems and deposit types (Hammarstrom and Zientek, 2016; appendix 3 in Day and others, 2016). Gold and silver occur in epithermal gold-silver (mercury) deposits that are part of the hydrothermal-volcanic rock associated system and in placer and paleoplacer gold deposits that are part of the surficial-mechanical (placer) mineral system. Bentonite deposits are part of the sedimentary system (formed during or after the conversion from sediment to sedimentary rock). Diamond occurs in diatreme-hosted diamond deposits that are part of the magmatic system (appendix 3 in Day and others, 2016). In this report, we base our assessments on the geologic models that have been developed for these mineral deposit types in the published literature, and as summarized elsewhere in this report (Hammarstrom and Zientek, 2016; appendix 3 in Day and others, 2016).

Mineral-Resources Potential

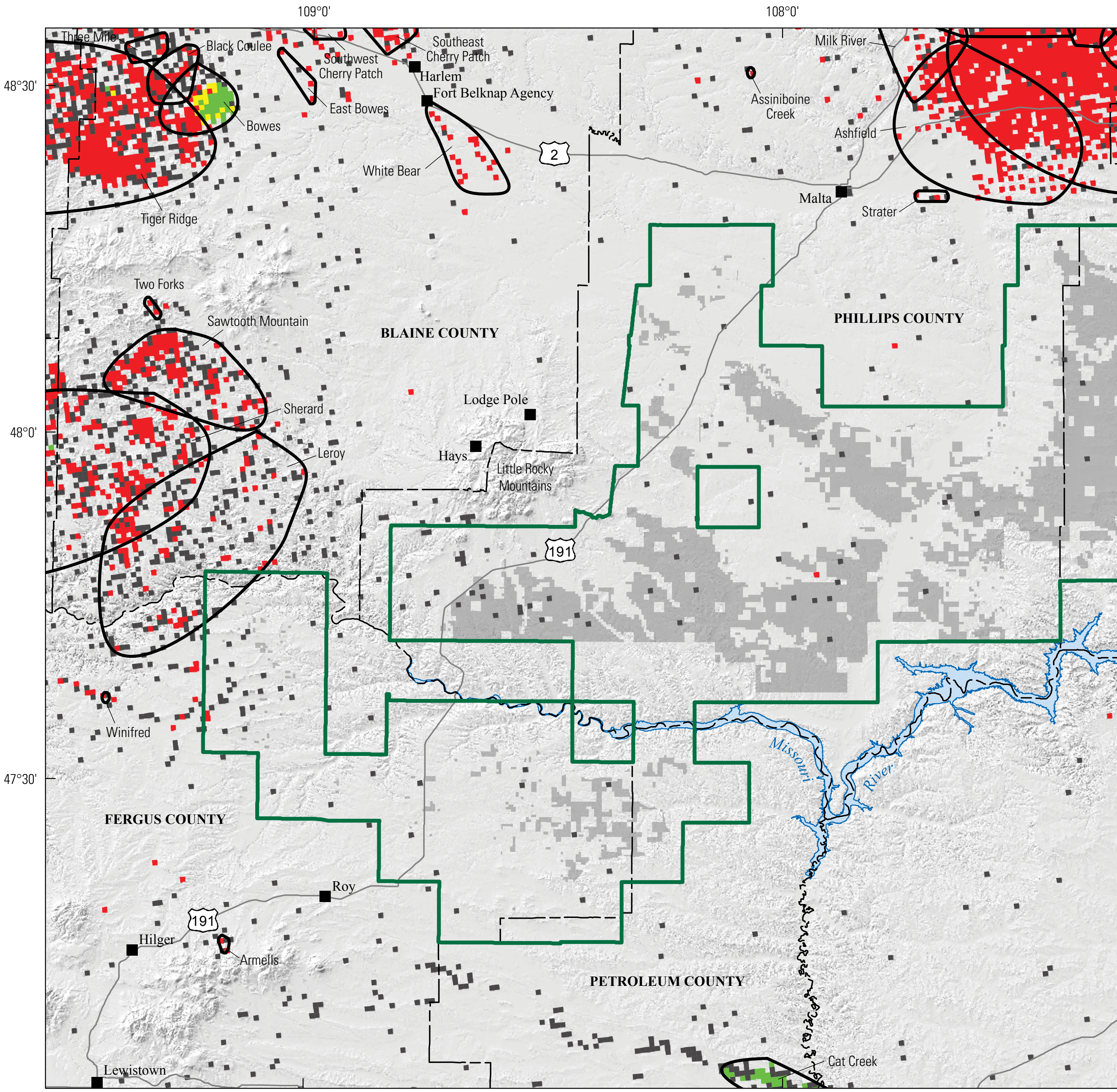
The BLM defines a "potential mineral resource" as the potential for the occurrence of a concentration of mineral resources. This term does not imply that there is potential for development or extraction of valuable mineral resources (Bureau of Land Management, 1985). The favorability for mineral resources can be evaluated by using multiple lines of evidence, including potential host rocks, geologic structure, alteration, geochemistry, geophysics, mineral deposits and occurrences, mineralogy, depth to basement, and other considerations (Bureau of Land Management, 1985).

The BLM uses qualitative rankings for mineral-resource assessments, ranking mineral-resource *potential* as high (H), moderate (M), low (L), no (O), and not determined (ND). For high potential, multiple lines of evidence indicate high potential for accumulation of mineral resources, and evidence indicates that mineral concentration has taken place. For moderate potential, multiple lines of evidence indicate a reasonable likelihood for accumulation of mineral resources. For low potential, the geologic environment and the inferred geologic processes indicate low potential for accumulation of mineral resources. "No potential" is used where the geologic environment, the inferred geologic processes, and the lack of mineral occurrences do not indicate potential for accumulation of mineral resources. For example, there is no oil potential in an area where the only rocks are unfractured Precambrian granite. "Not determined" is used where there is a lack of useful data, and this notation does not require a level-of-certainty qualifier (Goudarzi, 1984; Bureau of Land Management, 1985; appendix 2 in Day and others, 2016).

For mineral-resource assessments, the BLM recognizes four levels of *certainty*: A, B, C, and D, where A is the least certain, and D is the most certain (Bureau of Land Management, 1985). For level A, the available data are not adequate to support or refute the possible existence of mineral resources within the area. For level B, the available data provide indirect evidence to support or refute the possible existence of mineral resources. For level C, the available data provide direct evidence but are quantitatively minimal to support or refute the possible existence of mineral resources. For level D, the available data provide abundant direct and indirect evidence to support or refute the possible existence of mineral resources (Goudarzi, 1984; Bureau of Land Management, 1985; appendix 2 in Day and others, 2016).

Known Locatable Mineral Deposits

The BLM LR2000 database shows no active lode claims in the Focal Area and 411 closed lode claims (table 4). The lode claims occur in the western part of the study area, south of the Little Rocky Mountains, and predominantly represent claims that were staked for exploration for epithermal and diamond deposits (fig. 11). Figure 11*A* shows some active claims



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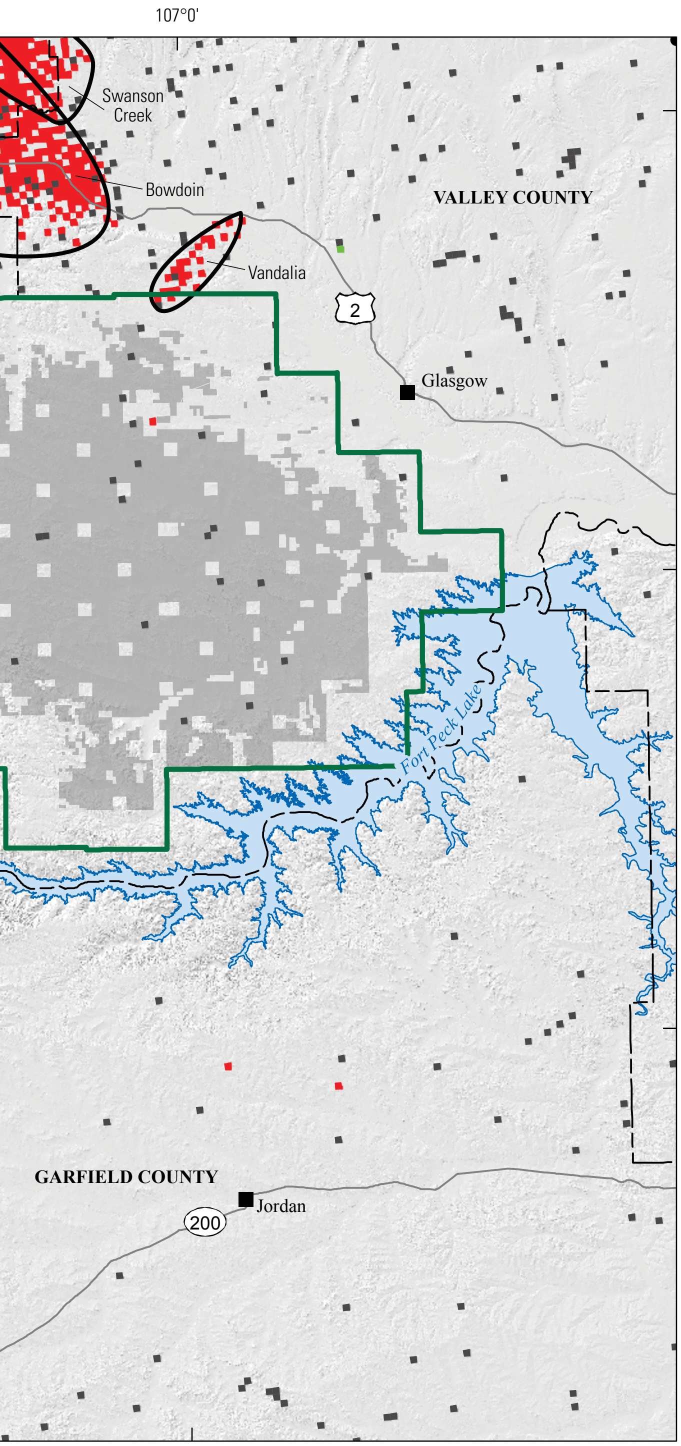
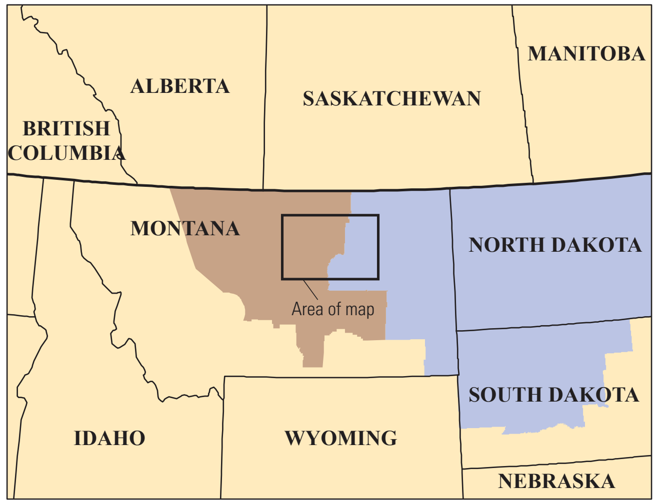
0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 10. Map showing State oil and gas provinces and exploration and well type (IHS Energy Group, 2016) for the North-Central Montana Sagebrush Focal Area. USGS, U.S. Geological Survey.





EXPLANATION

USGS study area boundary

Proposed withdrawal area

Oil and gas fields

Well type summary for 1/4 mile cells

Oil

Gas

Oil and gas

Dry

Oil/Gas Province (on index map only)

North Central-Montana

Williston Basin

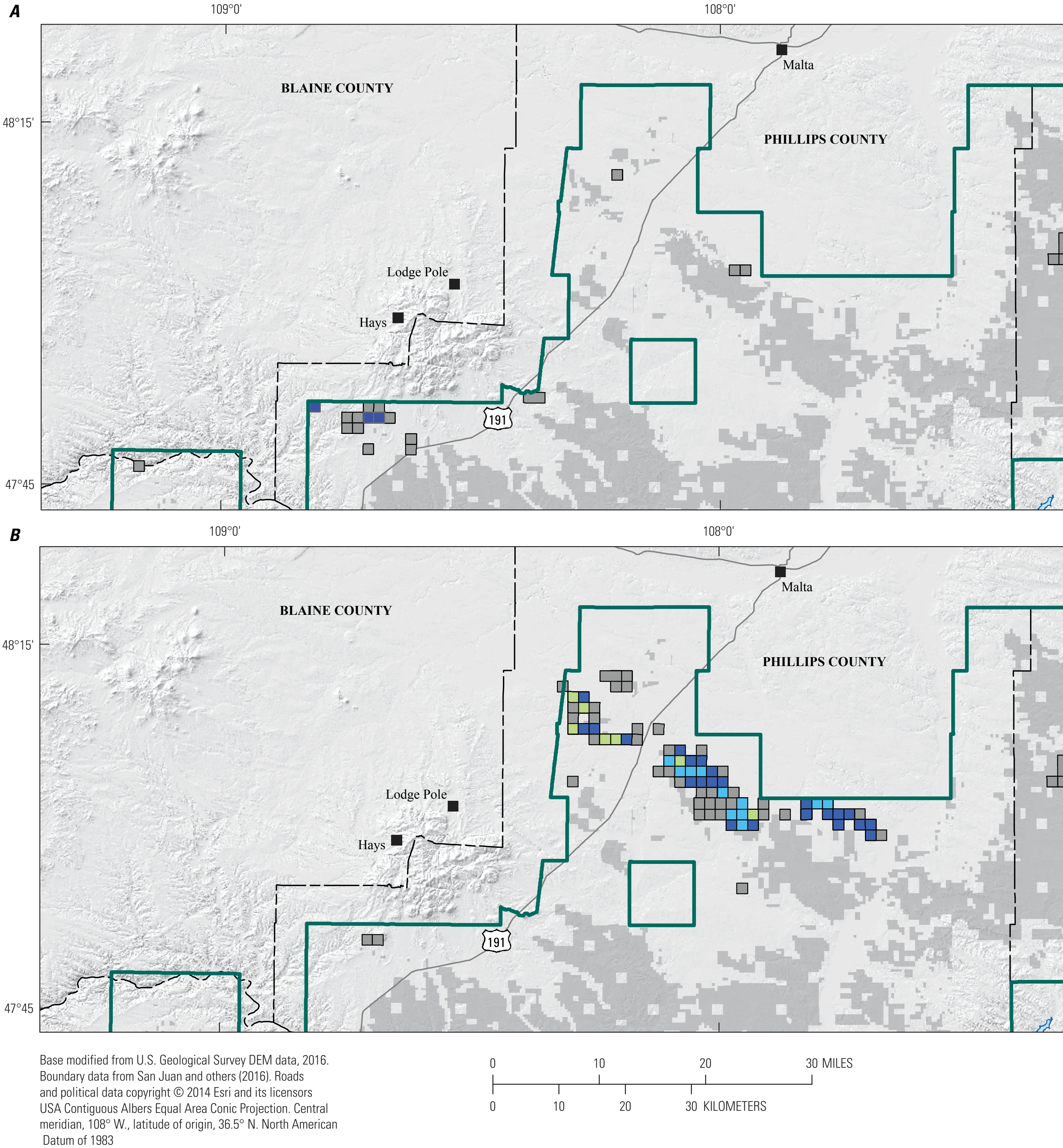
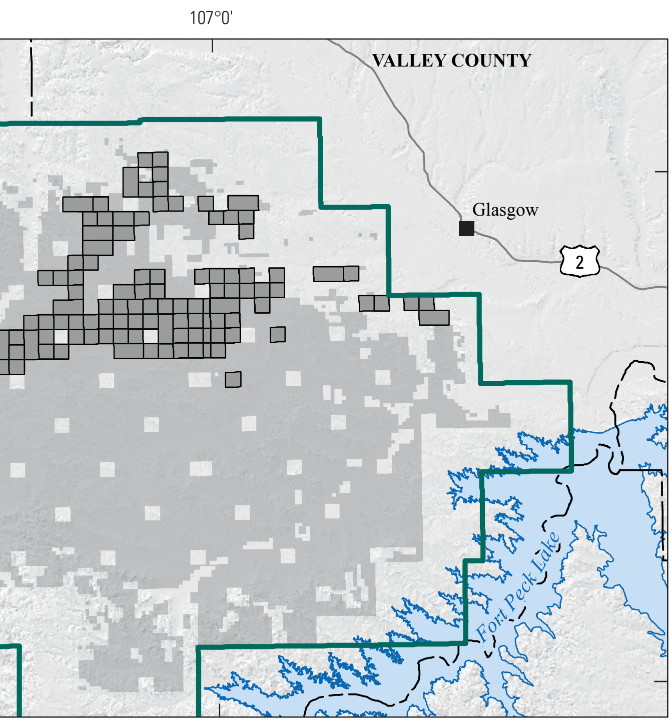
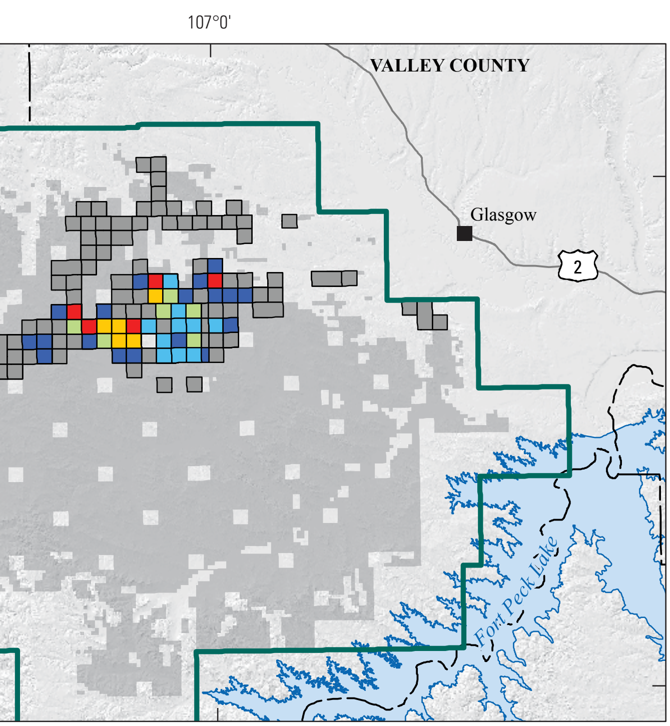
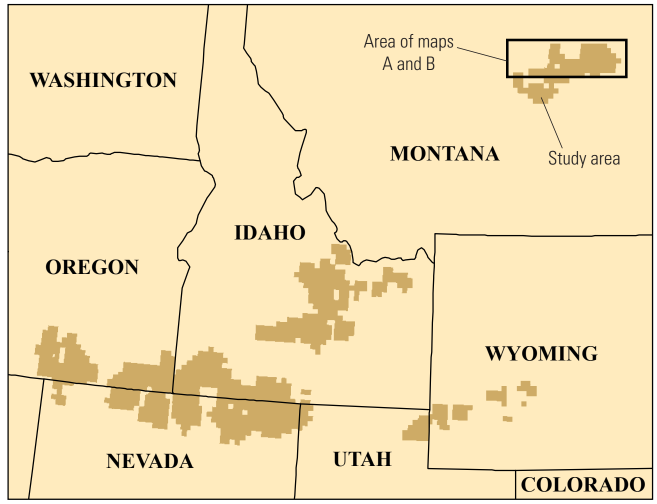


Figure 11. Maps showing active and closed mine claims for locatable commodities in the North-Central Montana Sagebrush Focal Area. *A*, Lode claims (modified from Dicken and San Juan, 2016a, b). *B*, Placer claims (modified from Dicken and San Juan, 2016a, b). USGS, U.S. Geological Survey.







EXPLANATION

- USGS study area boundary
- Proposed withdrawal area

Number of active mining claims

- 1 - 5
- 6 - 11
- 12 - 16
- 17 - 22
- 23 - 31
- Closed mining claims

in this area that occur within the study area, but lie outside the proposed withdrawal area.

The BLM LR2000 database shows 687 active placer claims in the Focal Area, and 1,079 closed placer claims (table 4). The majority of placer claims in the North-Central Montana Sagebrush Focal Area represent former and current exploration for bentonite deposits, and they occur generally in the northern part of the study area (fig. 11*B*).

Historic Production

Production of locatable minerals from the study area and nearby has come from epithermal deposits that produced gold and silver, and from bentonite deposits. Production figures and estimates for these deposit types are presented below, in the Hydrothermal-Volcanic Rock Associated System section, and the Bentonite section.

Mining Claims and Permits

The BLM LR2000 database shows six notices for the proposed withdrawal area of the North-Central Montana Sagebrush Focal Area (table 5). These notices are all closed, and there are no active notices in the proposed withdrawal area (table 6).

The BLM LR2000 database shows five plans of operations for the proposed withdrawal area of the North-Central Montana Sagebrush Focal Area (table 5). One plan of operations is authorized, two are pending, and two are closed (table 6). All active plans of operations in the proposed withdrawal area relate to bentonite (table 6; figs. 12, 13).

Table 4. Summary of mining claims for locatable minerals in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area.

[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]

Area	Active lode claims	Closed lode claims	Active placer claims	Closed placer claims
Cases containing proposed withdrawal area	0	411	687	1,079

Table 5. Summary of status and number of 43 CFR 3809 notices and plans of operations for locatable minerals in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area.

[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]

Permit type	Number of unique cases	Active	Authorized	Pending	Closed	Cancelled	Expired	Rejected	Withdrawn
Plans of operations	5	ND	1	2	2	ND	ND	ND	ND
Notices of intent	6	ND	ND	ND	6	ND	ND	ND	ND

Table 6. Active 43 CFR 3809 notices and plans of operations summarized by commodity in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area.

[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]

Commodity	Number of active notices	Number of active plans of operations
Clay, Bentonite	0	3

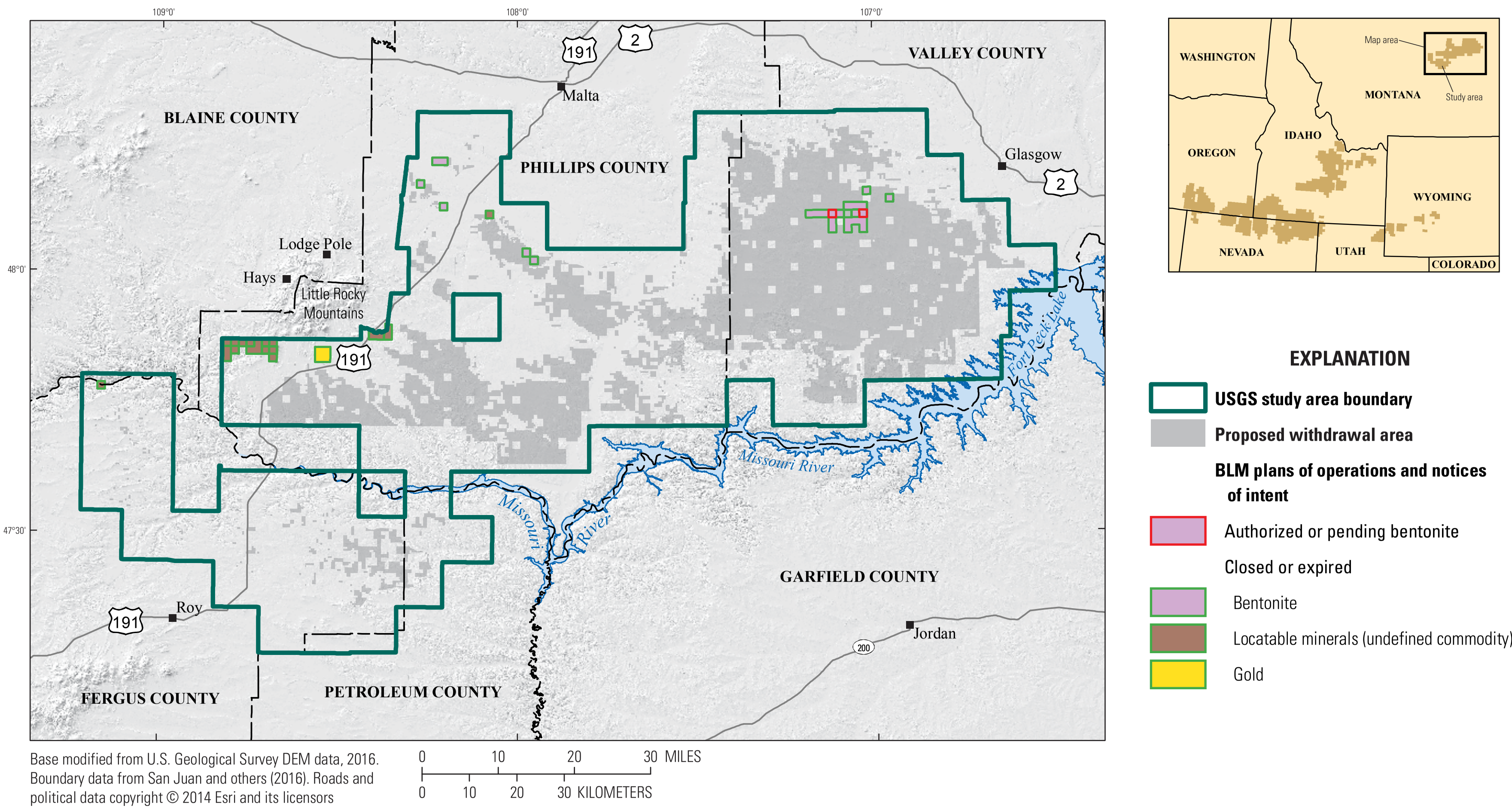


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Figure 12. Map showing 43 CFR 3809 notices and plans of operations for locatable commodities in the North-Central Montana Sagebrush Focal Area (modified from Dicken and San Juan, 2016a, b). BLM, Bureau of Land Management; USGS, U.S. Geological Survey.

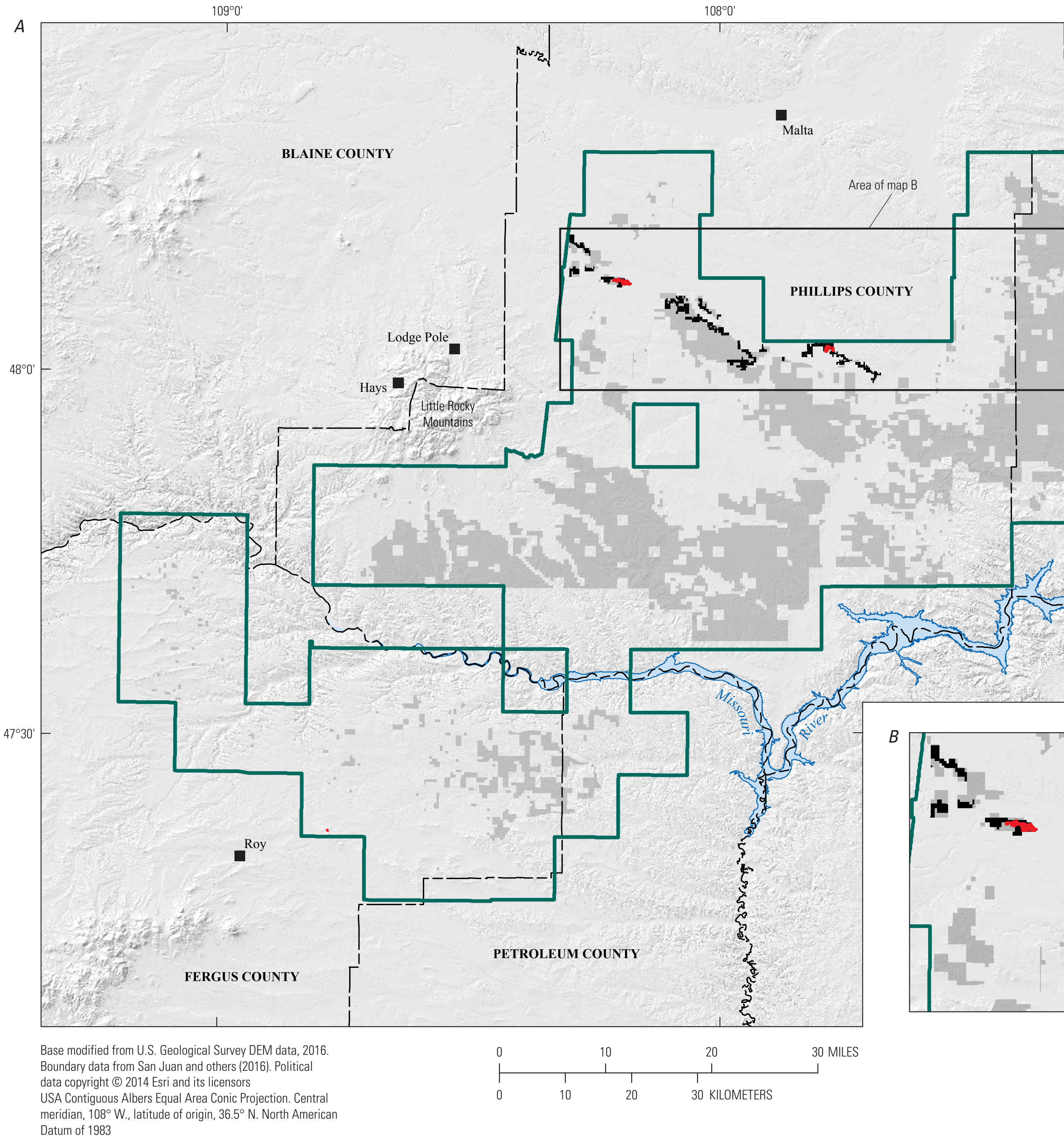
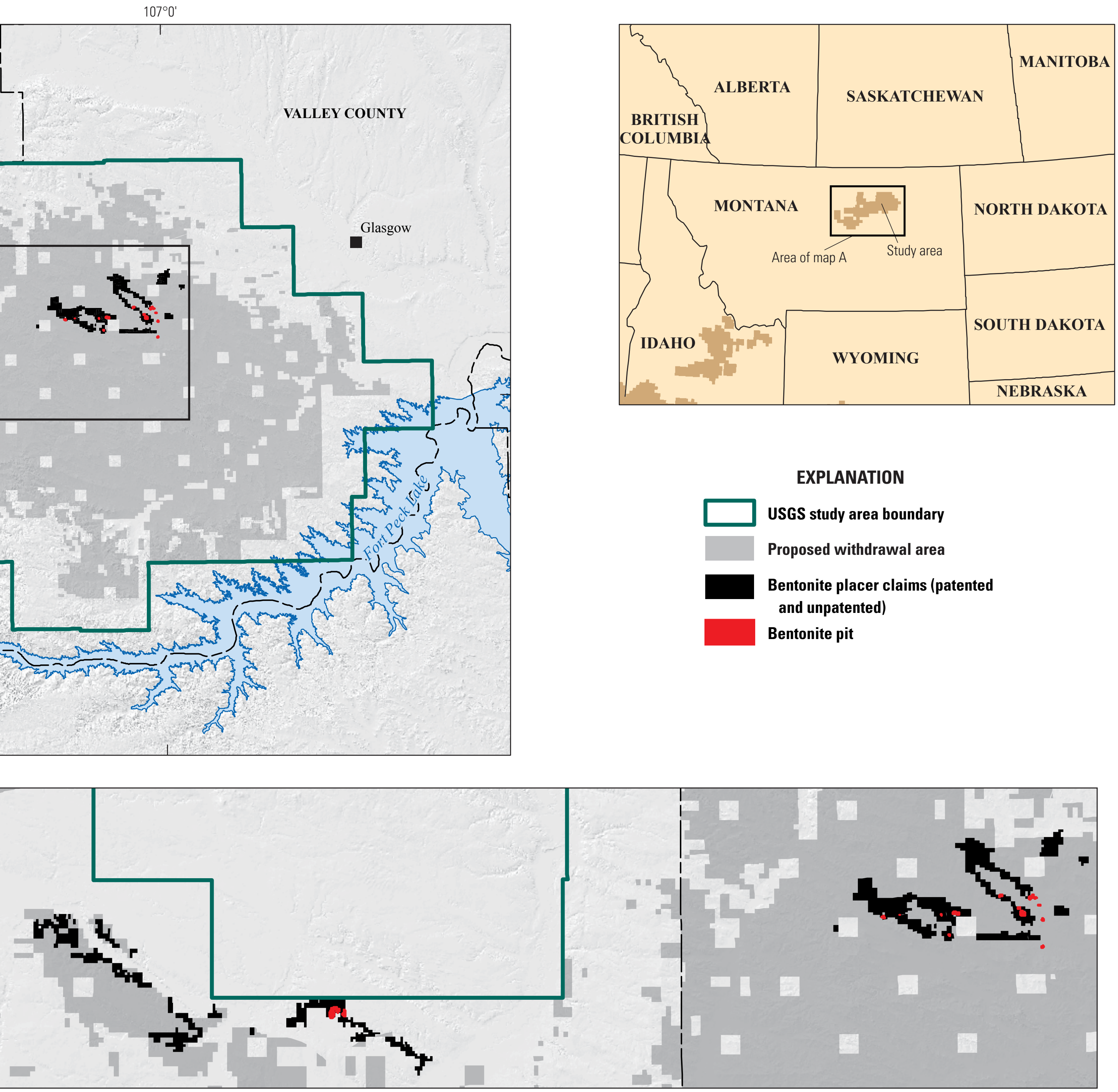


Figure 13. Maps showing bentonite claims and deposits for locatable commodities in the North-Central Montana Sagebrush Focal Area. *A*, The entire focal area. *B*, A detailed view of the area containing claims (Nathaniel Arave, Bureau of Land Management, Billings, Mont., written commun., 2016). USGS, U.S. Geological Survey.


107°0'
VALLEY COUNTY
Glasgow
Fort Peck Lake
MANITOBA
ALBERTA
SASKATCHEWAN
BRITISH COLUMBIA
MONTANA
NORTH DAKOTA
Area of map A
Study area
IDAHO
SOUTH DAKOTA
WYOMING
NEBRASKA
EXPLANATION
USGS study area boundary
Proposed withdrawal area
Bentonite placer claims (patented and unpatented)
Bentonite pit

Metallic Locatable Minerals

Based on geologic setting, past production, and current and past exploration activities, the only metallic minerals that are potentially locatable in the North-Central Montana study area are gold and silver, which may occur in epithermal and placer deposits in the study area. There are no records of production from any other types of metallic mineral deposits in the study area, and to the best of our knowledge, there has been no significant exploration for any other types of metallic mineral deposits in the study area.

The sections below describe epithermal and placer deposits, and then estimate the potential and certainty for locating these types of deposits in the study area. For the sake of completeness, we also include a brief discussion of other types of hydrothermal deposits that commonly occur with epithermal deposits, and we evaluate whether these other deposits, such as porphyry and skarn deposits, might occur in the study area.

Hydrothermal-Volcanic Rock Associated System

The hydrothermal-volcanic rock associated system contains a number of different types of mineral deposits, including epithermal gold-silver (mercury) deposits (appendix 3 in Day and others, 2016), which are referred to herein as epithermal deposits; this is the only deposit type in this system that is known to occur near the study area. Epithermal deposits form within 1 km of the surface of the Earth, and they typically occur in volcanic arcs at convergent plate margins in continental and oceanic settings, in continental-margin back arcs, in rifts, and in intraplate environments (Hedenquist and Lowenstern, 1994; Sillitoe and Hedenquist, 2003; Sillitoe, 2008). Epithermal deposits form vein, stockwork, disseminated, and replacement deposits that are principally mined for gold and silver. Byproducts may include lead, zinc, copper, and (or) mercury, but in most deposits, these are not recovered (Simmons and others, 2005).

Epithermal deposits most commonly occur in alkaline to calc-alkaline volcanic rocks and hypabyssal intrusions that range in composition from mafic to felsic. Hosts for some deposits are silica-undersaturated, highly alkali-rich (Na_2O + K_2O) rocks ranging from felsic phonolites to ultramafic lamprophyres (Jensen and Barton, 2000). Most epithermal deposits are Cenozoic in age, which reflects preferential preservation of these shallowly formed deposits in tectonically active regions (Kesler and Wilkinson, 2009). Epithermal deposits have characteristic ore and alteration mineralogy, and these produce characteristic geochemical and geophysical signatures (for example, Lindgren, 1933; Warren and others, 2007; Morrell and others, 2011; Saunders and others, 2014), as summarized in appendix 3 of Day and others (2016).

Geology and Occurrence in the Study Area

There are no known epithermal deposits in the study area. However, the Zortman and Landusky deposits in the Little Rocky Mountains are within 25 km of the study area, and together, they form a large epithermal deposit (fig. 14). From the 1880s to 1951, underground mining of high-grade epithermal veins in the Little Rocky Mountains produced 380,000 ounces (oz) of gold (Wilson and Kyser, 1988). Mining resumed in the area in the 1970s with the introduction of gold and silver recovery from heap leaching using cyanide recovery techniques. This led to recovery of an additional 2.5 million oz (Moz) of gold and 20.7 Moz of silver from the Zortman and Landusky deposits (Maehl, 2002), so together the Zortman and Landusky deposits form an orebody that is nearly world-class (>3.2 Moz of gold, Singer, 1995) in size.

The deposits occur in quartz monzonite and syenite that are part of the suite of Tertiary alkaline igneous rocks in the Little Rocky Mountains (Knechtel, 1959). Normative abundances of quartz, orthoclase, and albite calculated from the whole-rock chemical compositions of unaltered intrusive rocks from the Zortman-Landusky mine areas yield alkali syenite, quartz syenite, and quartz monzonite compositions (Wilson and Kyser, 1988). Hydrothermal alteration includes widespread illite and pyrite alteration and more localized silicification and quartz stringers, and the groundmass of altered intrusive rocks contains variable amounts of pyrite, kaolinite, montmorillonite, and fluorite (Wilson and Kyser, 1988; Rogers and Enders, 1990; Wampler, 1994). In the unweathered rock, the vast majority of the gold occurs in pyrite, and minor gold also occurs in telluride minerals and electrum or as native gold. The gold that resides in pyrite and in telluride minerals is not recoverable by conventional cyanide recovery techniques, so the Zortman and Landusky deposits mined only oxidized material where native gold occurs in fractures with hematite, goethite, and, more rarely, jarosite (Wilson and Kyser, 1988; Williams, Gabelman, and others, 2009).

Potential for Occurrence

The potential for epithermal deposits in the Little Rocky Mountains has been previously assessed by delineation of a Known Mineral Deposit Area (KMDA) by U.S. Bureau of Mines geologists and engineers for the Inventory of Land-Use Restraints Program (ILURP), which was active from 1983 through 1995 (Parks and others, 2016a, b). These tracts are similar to tracts that were previously delineated by Bateman and Lutz (1976) and Box and others (1996). These tracts, which are outside the study area, include the Zortman and Landusky deposits, which together produced nearly 2.9 Moz of gold since the 1880s.

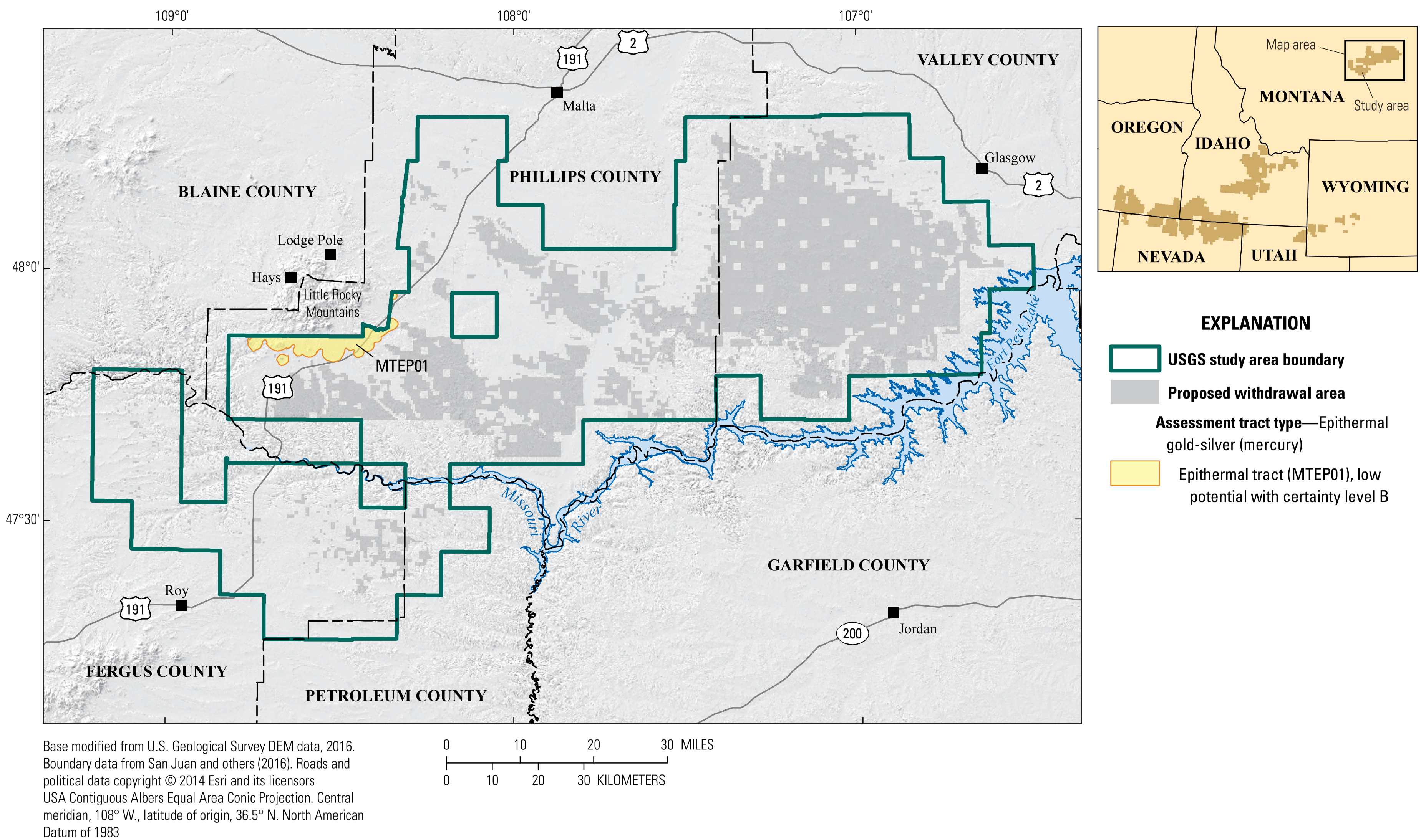


Figure 14. Mineral potential map for epithermal deposits in the North-Central Montana Sagebrush Focal Area. USGS, U.S. Geological Survey.

Epithermal Deposits: Tract MTEP01 (Epithermal)

This is a low-potential, certainty level B tract for epithermal deposits that envelops the area that is likely underlain by the igneous rocks of the Little Rocky Mountains (appendix 2; fig. 14). The MTEP01 tract lies within the study area, but the tract overlies only one small area that is specifically proposed for withdrawal (fig. 14; San Juan and others, 2016).

About 20 named domes occur in the low hills on the southwest, south, and southeast flanks of the Little Rocky Mountains. The National Uranium Resource Evaluation (NURE) aeromagnetic data show magnetic anomalies that indicate that the low hills likely overlie concealed igneous intrusive rocks, similar to those exposed in the Little Rocky Mountains (Hill and others, 2009). In the main coalescing-dome complex of the higher part of the Little Rocky Mountains, syenite porphyries are mostly in fault contact with post-Cambrian formations, implying that the depth of bed-parallel intrusion was in or below the Cambrian formations. Only one outlying dome has exposed syenite porphyry, and there, the porphyry occurs beneath Cambrian strata (Knechtel, 1944, 1959). Therefore, the intrusions that underlie the domes in the study area are presumably sill-like or laccolithic, and are probably in or below the Cambrian sedimentary rocks.

Some of the domes were drilled for oil and gas prior to 1944, and are shown on the Knechtel (1944) map. Nine drill holes were relatively shallow (depth 250 m or less); three holes (depth 300–600 m) reached the Mississippian Mission Canyon Limestone. Syenite porphyry intrusions were not encountered in those depth ranges. Gas was found in three holes (Knechtel, 1944).

Part of the MTEP01 tract is covered by high-resolution aeromagnetic data that were acquired by Anaconda Minerals Company in 1981 (Anderson and others, 2016). These data clearly indicate that intrusions underlie domes in the sedimentary rocks at the outer margins of the Little Rocky Mountains. However, these data do not indicate whether any of these intrusions are altered, so they do not increase the certainty or potential of the tract.

This is a low-potential tract because there is evidence that intrusive rocks that host nearby epithermal deposits occur within the tract boundary; however, except for one exposure, those intrusive rocks lie at depth in the study area (fig. 4), and there are no data to indicate that those intrusive rocks are altered or mineralized.

At the time of this report, there do not appear to be any active claims, notices, or plans of operations related to potential epithermal mineralization inside the study area, despite activity in the past. At the time of this report, there is a ban on extraction of gold by cyanide recovery techniques in the State of Montana. Heap leaching is the preferred extraction technique for these types of deposits, so the ban on extraction of gold by cyanide recovery techniques likely contributes to the reduced exploration activity.

Economic Analysis of the Deposit Types

On a global basis, epithermal deposits are an important source of gold and silver (Simmons and others, 2005; Saunders and others, 2014). The Zortman-Landusky District has large epithermal deposits, and therefore the igneous rocks of the Little Rocky Mountains that lie outside the study area have had very significant past production of gold and silver. However, because the potential host rocks for epithermal deposits lie almost exclusively under cover in the study area, and because there are no data to indicate that these rocks are altered or mineralized, the potential for epithermal deposits is considered low within the study area. Furthermore, the vast majority of that area with low potential is outside of the proposed withdrawal area (fig. 14). Moreover, the current ban on extraction of gold by cyanide recovery techniques in the State of Montana would have to be lifted before mining of epithermal gold-silver deposits could be considered in the area. Because the potential for epithermal deposits is considered to be none for most of the proposed withdrawal area, and because of the current ban on cyanide recovery techniques, it is unlikely that extraction of gold and silver from epithermal deposits in the proposed withdrawal area could have a significant economic impact in the future.

Other Hydrothermal Mineral Deposits

Epithermal gold deposits form from hydrothermal fluids at shallow levels in the Earth's crust in areas that are characterized by active volcanism, active plutonic rock formation, or both. Other hydrothermal deposits, such as porphyry and skarn deposits, form from magmatic hydrothermal processes in this environment, so the potential for these other deposit types must be considered herein.

There is little contact metamorphic skarn in the Little Rocky Mountains, even where intrusive rocks are in contact with carbonate rocks (Weed and Pirsson, 1896; Wampler, 1994). Furthermore, we are not aware of any occurrences in the Little Rocky Mountains that would indicate that there may be skarn mineralization in the area (Meinert and others, 2005). Similarly, there are no reported occurrences of porphyry copper, porphyry molybdenum, or iron oxide copper-gold mineralization in the Little Rocky Mountains, even though alkaline intrusive rocks can host large porphyry and iron oxide copper-gold deposits (Seedorff and others, 2005; Williams and others, 2005). Because there are no reported occurrences of porphyry or skarn mineralization in the Little Rocky Mountains where the main mass of intrusive rocks are exposed, the potential for these deposits inside the study area is considered to be none.

It is probable that the sedimentary rocks inside the study area conceal latest Cretaceous to Paleocene intrusive igneous rocks, and that these rocks may contain magmatic hydrothermal mineralization. However, depth to source modeling of the available aeromagnetic data indicates that the majority of the magnetic anomalies can be attributed to variability in basement rocks at more than 1 km depth (Anderson and Ponce, 2016). The exception to this is an area 45 km southeast of the Little Rocky Mountains that may have magnetic sources as shallow as 500 m. However, with (1) no supporting evidence, (2) no known surface structure or alteration effects from a shallow intrusion, (3) no subsurface data that could allow assessment of potential mineralization within this possible intrusive complex, and (4) no evidence of deep-seated hydrothermal mineralization in the area, such as porphyry, iron oxide copper-gold, or skarn deposits, we lack any basis on which to draw a tract over this possible buried intrusive complex.

Surficial-Mechanical (Placer) Mineral System

The surficial-mechanical (placer) mineral system contains a number of different types of mineral deposits (appendix 3 in Day and others, 2016). Placer and paleoplacer gold deposits, which are referred to herein as placer deposits, occur in the study area, but other types of deposits in the surficial-mechanical (placer) mineral system are not known to occur within the study area. Placer deposits generally occur as alluvial deposits and as coastal deposits; the latter are briefly described as "heavy mineral placer" deposits in appendix 3 of Day and others (2016). Placer deposits are a principal source of zirconium and a primary source of titanium for the TiO_2 pigments industry, but these elements are almost entirely produced from heavy-mineral sands deposited in coastal environments (Force, 1991; Garnett and Bassett, 2005; Van Gosen and others, 2014). Heavy mineral placers are significant sources of gold in some areas of the Unites States, such as Alaska, and also in some countries elsewhere (Yeend and Shawe, 1989; Youngson and Craw, 1995; Jones and others, 2015).

Mineral Description

Although placer deposits can be important sources for a variety of minerals such as ilmenite ($FeTiO_3$), rutile (TiO_2), zircon ($(Zr,Hf,U)SiO_4$), monazite ($(Ce,La,Y,Th)PO_4$), xenotime (YPO_4), garnet, cassiterite (SnO_2), sillimanite (Al_2SiO_5), staurolite ($Fe_2Al_9Si_4O_{23}(OH)$), and platinum-group minerals, the majority of the alluvial placer deposits worldwide are worked to recover gold. Given the occurrence of the large epithermal gold-silver deposits of the Zortman-Landusky District, just outside the study area, the placer gold potential of the study area must be considered.

Geology and Occurrence in the Study Area

From the early 1880s to 1951, placer deposits in the Zortman-Landusky District produced 326 oz of gold (10 kg), which is three orders of magnitude less than the production from lode deposits (380,000 oz of gold) during the same time period (Rogers and Enders, 1990). The very low yields from placer deposits reflect the fact that the vast majority of the gold in nearby epithermal deposits occurs in solid solution in pyrite and in telluride minerals, and not as native gold or electrum (Wilson and Kyser, 1988), which are required for productive gold placer deposits.

At this time, there do not appear to be any active claims, notices, or plans of operations related to potential placer deposits inside the study area.

Potential for Occurrence

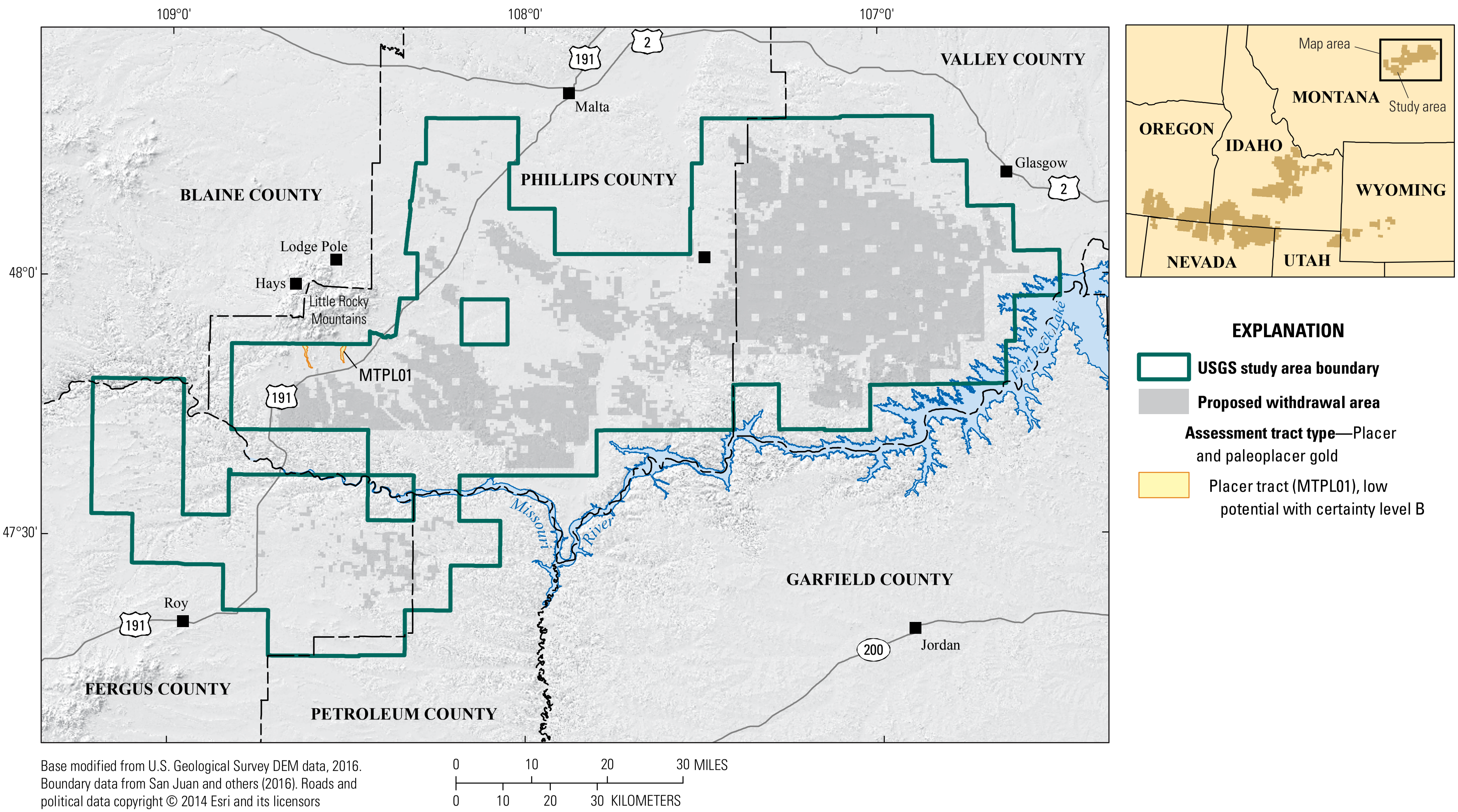
Placer deposit sites in the Little Rocky Mountains were described by Bateman and Lutz (1976). To the best of our knowledge, there are no previous assessments for placer deposits in the study area (Parks and others, 2016a, b).

Placer Deposits: Tract MTPL01 (Placer)

Tract MTPL01 (Placer) is a low potential, certainty level B tract for placer deposits (appendix 2). The tract was constructed by enveloping Quaternary alluvial deposits that extend downstream for a distance of 10 km from potential lode sources of gold at the Zortman and Landusky deposits (figs. 15, 16). This tract does not overlie any areas that are specifically proposed for withdrawal (fig. 15; San Juan and others, 2016).

Economic Analysis of the Deposit Types

Although placer deposits can be an important source of gold, the lack of significant past production and the lack of suitable source material to form large and productive deposits suggest that the potential for economically significant placer deposits in the study area is low to none. Because the placer tracts do not overlie any area that has been proposed for withdrawal, the potential for economically significant placer deposits in the proposed withdrawal area is considered to be none.



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 15. Mineral potential map for placer deposits in the North-Central Montana Sagebrush Focal Area (modified from Knechtel, 1959; Montana State Library, 2016a). USGS, U.S. Geological Survey.

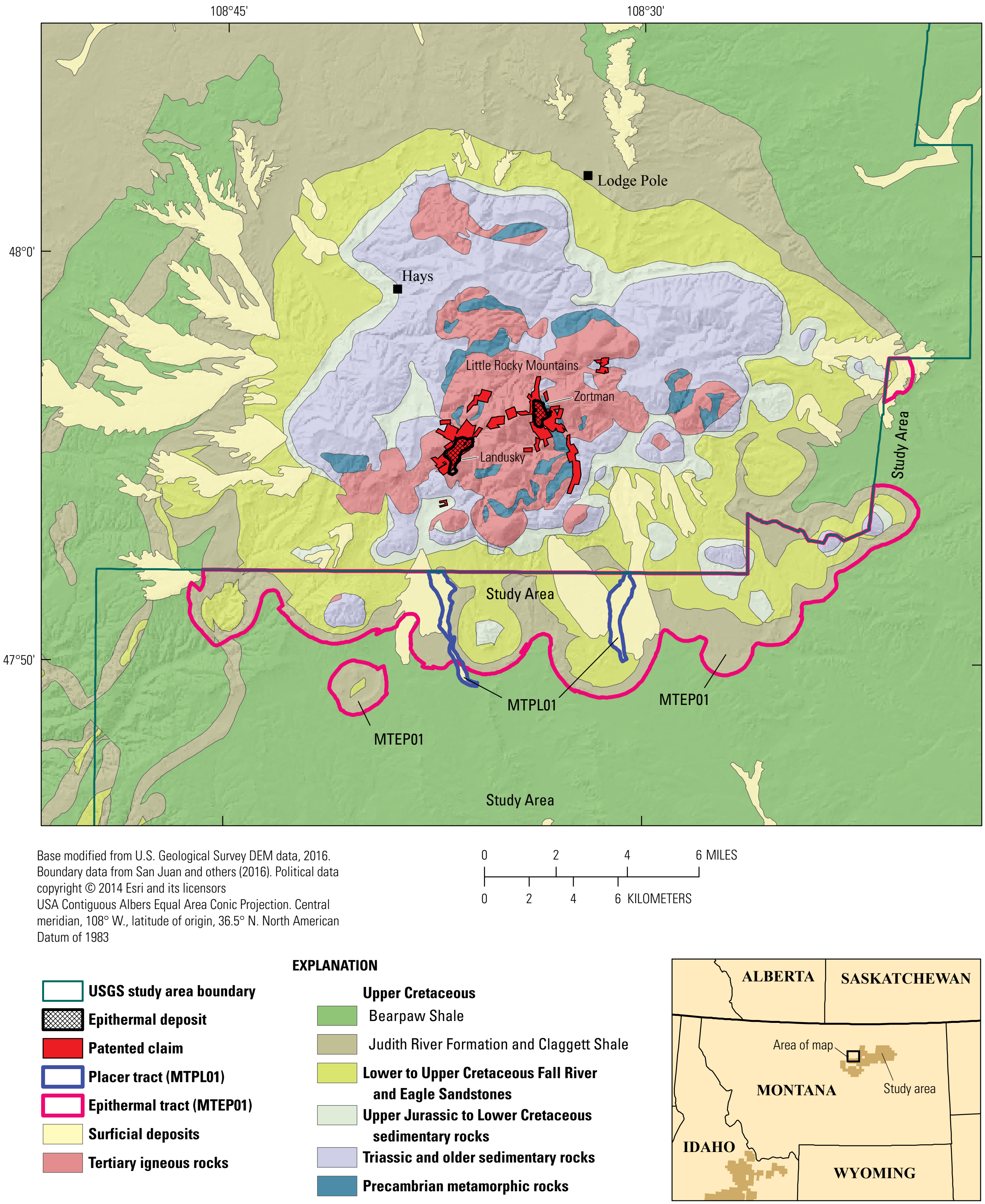


Figure 16. Map showing geology of Little Rocky Mountains and the epithermal and placer tracts in the northwest part of the North-Central Montana Sagebrush Focal Area (modified from Knechtel, 1959; Vuke and others, 2007). USGS, U.S. Geological Survey.

Nonmetallic Locatable Minerals

Based on geologic setting, past production, and current and past exploration activities, the only nonmetallic minerals that are potentially locatable in the North-Central Montana study area are bentonite and diamond, which may occur in deposits in the study area. This section describes these two types of deposits, and provides estimates of the potential and certainty for locating these types of deposits in the study area.

Sedimentary System (Formed During or After the Conversion from Sediment to Sedimentary Rock): Bentonite Deposit Type

Bentonite is a claystone formed by the chemical alteration of glassy volcanic ash (Neundorf and others, 2005) most commonly found interbedded with shallow marine shales and limestones. The most common clay minerals in bentonite are members of the smectite mineral group, especially the mineral montmorillonite ($(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$). The properties of bentonite are dictated by the properties of the dominant clay minerals (Eisenhour and Brown, 2009). Bentonites are divided into sodium-bentonite (dominated by sodium montmorillonite), which is also called swelling bentonite, and calcium-bentonite (dominated by calcium montmorillonite), which is non-swelling bentonite. Other varieties of bentonite are dominated by other smectite minerals, for example, hectorite ($Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$) (Harben and Kužvart, 1996; Harben, 2002). Sodium-bentonite can absorb large amounts of water and form viscous, thixotropic clay. In contrast, calcium-bentonite has low water absorption and swelling capabilities and cannot stay suspended in water.

Bentonite is an important raw material required for the extraction and production of energy and steel resources and is called the “clay with 1,000 uses” (Feick, 2016). Bentonite is commonly used in drilling fluids, in metal castings, in pet-waste absorbents, and as a binder for making iron-ore pellets (Eisenhour and Brown, 2009). It is also used as an agent for clarifying and removing colors from oils, as a desiccant, as a flocculent for papermaking, and in sealants (Grim and Güven, 1978; Inglethorpe and others, 1993; Eisenhour and Brown, 2009; Dlamini, 2015).

Mineral Description

Bentonite forms by the alteration of volcanic ash and tuffs deposited in shallow oceans or brackish ponds and lakes (Eisenhour and Brown, 2009; Wilson, 2013). Sodium bentonite-type clay deposits are derived from ash that was deposited in shallow marine environments. Calcium bentonite-type clays form in freshwater settings (Alther, 2004). Bentonite layers commonly contain trace amounts of minerals, such as feldspar, biotite, quartz, and pyroxene that were accessory phases in the original volcanic material. Several key processes are necessary to form an accumulation of bentonite that has economic potential (Wilson, 2013). First, ash and tuff of rhyolitic to dacitic composition are deposited in shallow saline waters. During diagenesis, glassy material in the ash and tuff are chemically altered to montmorillonite and other clays. Beds are typically less than 1 m thick. The bentonite layers must be exhumed; only those layers within about 15 m of the surface form deposits that can be developed.

Bentonite is mined from open pits that rarely extend to depths of 15 m. Maximum strip ratios are about 10:1. Bentonite mined from open pits is blended, ground, dried, and processed into various products at mills. Close proximity to transportation routes, such as highways and railroads, is an important consideration in determining if a near-surface bentonite layer can be economically developed (Miller and others, 1979; Eisenhour and Brown, 2009; Sutherland and Drean, 2014).

Both the grade and the quality of the bentonite must be considered for different industrial applications (Inglethorpe and others, 1993). The grade is defined as the smectite content of the bentonite, whereas quality is related to the physico-chemical properties of the clay, and is a measure of likely industrial performance.

Geology and Occurrence in the Study Area

Cretaceous bentonite deposits occur in marine shales that accumulated in shallow seas covering the present-day midcontinent region of North America (Western Interior Seaway; fig. 17). Deposits of bentonite are found in Wyoming, Montana, South Dakota, Alberta, and Saskatchewan in rocks of the Colorado Group (Lower Cretaceous) and Montana Group (Upper Cretaceous), and their equivalents. From lowest to highest in the Cretaceous System, layers of bentonite in the Hardin District of Montana are designated from A through W, with some prominent layers having proper names (fig. 18). Most sodium bentonite production in the United States is from the Clay Spur Bentonite Bed in the Upper Cretaceous Mowry Shale in Wyoming and adjacent parts of Montana. In other places in Montana, sodium bentonite has been mined from the (1) Soap Creek Bentonite Bed in the Cody Shale, Hardin District; (2) X and Y beds in the Bearpaw Shale in the Malta and Glasgow areas; and (3) X and Y beds in the Bearpaw Shale in the Ingomar-Vananda area (fig. 17; Hosterman and Patterson, 1992). The North-Central Montana Sagebrush Focal Area largely covers the Malta and Glasgow areas of Hosterman and Patterson (1992).

The Late Cretaceous Bearpaw Shale of the Montana Group is a dark-gray montmorillonite-rich shale that crops out over much of northern Montana. A bentonite-rich interval in the Bearpaw Shale is recognized in stratigraphic sections ranging from north-central Montana to central Wyoming. In a dry oil and gas hole southeast of the Little Rocky Mountains (fig. 5), there are several beds of bentonite in a 6-m-thick zone in the Bearpaw Shale, about 37 m above the top of the Judith River Formation. Knechtel (1959) proposed that this interval is approximately equivalent to the Monument Hill Bentonitic Member of the Pierre Shale of the Black Hills region

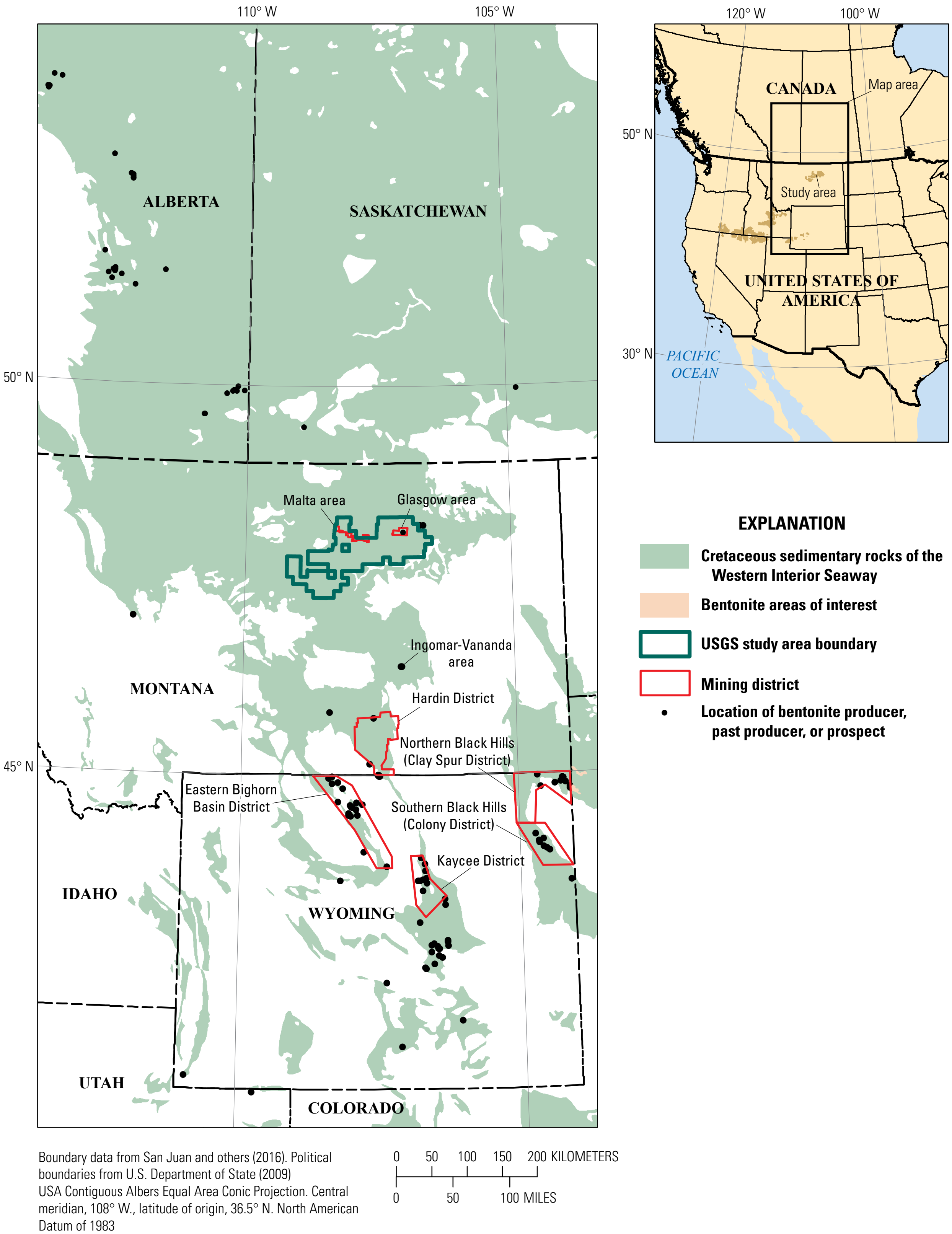


Figure 17. Map showing extent of Cretaceous sedimentary rocks that formed in the Western Interior Seaway with locations of mining districts and bentonite deposits, north-central United States and south-central Canada. Geology modified from Garrity and Soller (2009). Mining districts from Knechtel and Patterson (1956), Hosterman and Patterson (1992), and Sutherland and Drean (2014). Bentonite locations with production from U.S. Geological Survey (2016a). USGS, U.S. Geological Survey.

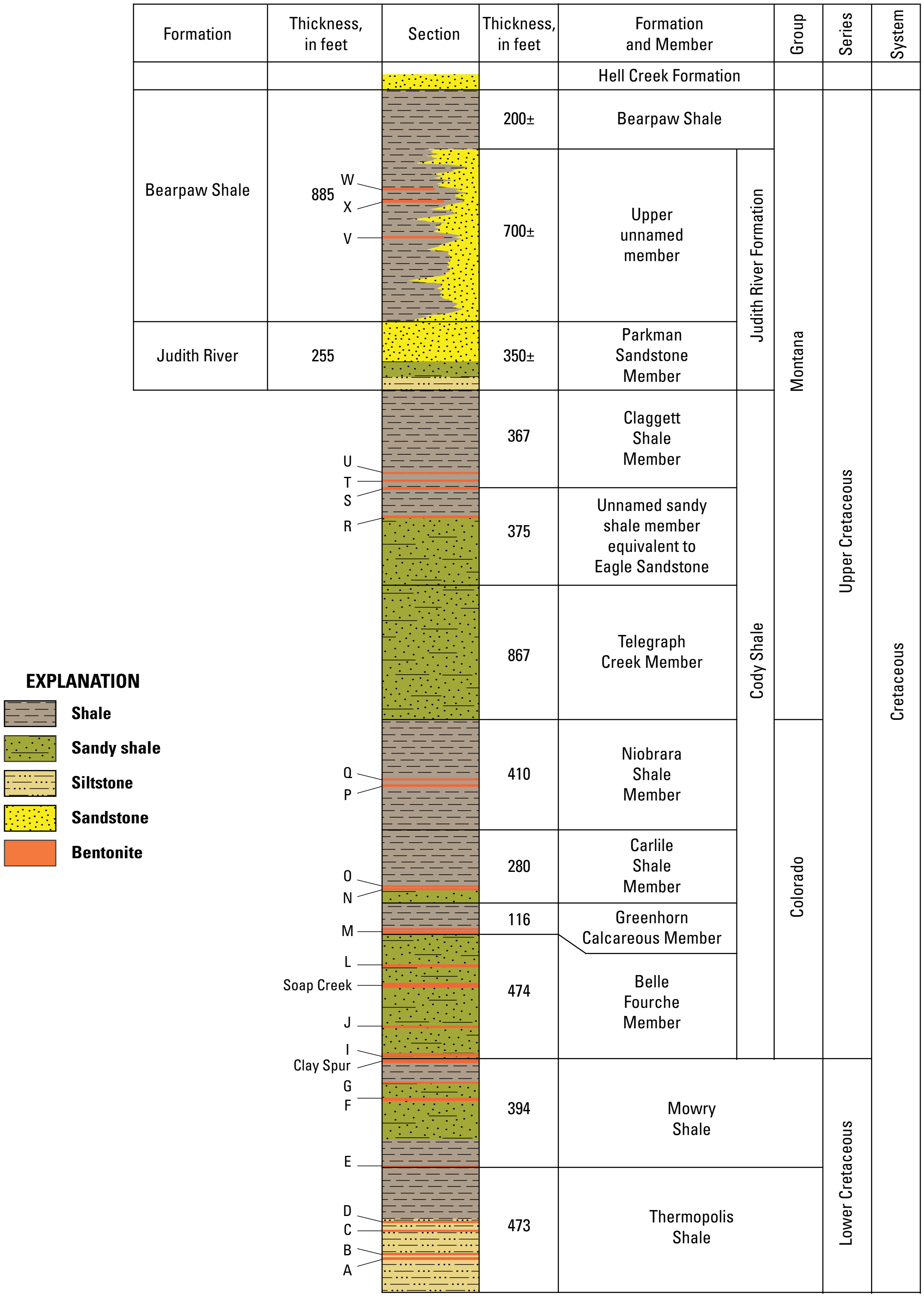


Figure 18. Stratigraphic column showing lithology with bentonite layers in the Hardin District, Montana. Modified from Knechtel and Patterson (1956).

and also to a bentonite-rich part of the Bearpaw Shale in the Hardin District, Montana (fig. 17). The extraordinary lateral continuity of the bentonite-bearing interval in the middle part of the Bearpaw Shale in Montana is shown on a section that runs west to east across central and eastern Montana, between the Dearborn River and the Porcupine Dome (fig. 19, section *A–A*'; Gill and Cobban, 1973). The bentonitic interval is likely correlative with the bentonite beds in the medial part of the Bearpaw Shale in the Kaycee District, Wyoming, almost 470 km to the south (figs. 17, 20).

Within the bentonitic interval of the Bearpaw Shale, two prominent bentonite beds are exposed in two regions in the northern part of the study area (fig. 21*A*). These beds are the most important accumulations of bentonite in the focal area. In the western area (Malta), the two beds are exposed for about 48 km on strike along Beaver Creek, Big Warm Creek, and Wild Horse Creek in Phillips County, about 40 km south of Malta. To the east, in the Glasgow area, beds extend about 21 km on strike and are exposed along Brazil Creek and the North and South Forks of Little Beaver Creek in Valley County, approximately 24–32 km west-southwest of Glasgow.

To the south, in the Charles M. Russell National Wildlife Refuge, a laterally continuous bentonite bed, named the Sipa-ryann bed, occurs approximately 24–61 m above the base of the Bearpaw Shale (fig. 21*B*; Miller and others, 1979). The bed crops out for at least 48 km along strike, from the west end of the refuge to the east. Near the west end of the refuge, the bed is 0.3 m thick; farther east, it is as much as 1.8 m thick. This bed is certainly within the 6-m-thick interval containing bentonite beds in the Bearpaw Shale described by Knechtel (1959) and may correlate with the two distinct bentonite beds in the Malta and Glasgow areas (Miller and others, 1979).

Also within the Charles M. Russell National Wildlife Refuge, Miller and others (1979) described and sampled bentonite layers and montmorillonite-rich silty shales within the Fox Hills and Hell Creek Formations, upsection of the Bearpaw Shale. Some of these layers could be equivalent to the volcanic ash near Linton, North Dakota (Manz, 1962). Within the refuge, these units appear to lack lateral continuity, are thin, and are siltier than the thicker bentonite beds in the Bearpaw Shale.

Geology of the Bentonite Beds in the Malta and Glasgow Areas

The Malta and Glasgow areas are underlain by Bearpaw Shale, though it is covered, in part, by alluvial and glacial deposits. In areas where bedrock is exposed and bentonite is weathered, it has a characteristic “popcorn texture” that can be distinguished at ground level. In areas of gentle dip, Berg (1969) noticed that beds of bentonite form small terraces because of their resistance to erosion, and that some exposures of bentonite can be traced by their lack of vegetation and by a color difference with surrounding rocks. Areas of hummocky glacial till and alluvial cover are readily distinguished in most areas. With some background knowledge, the distribution of the bentonite beds can be mapped on satellite-images (fig. 22).

Mineral reports for mineral patent applications provide the most information about the geology of the two prominent bentonite beds, X and Y, in the Malta area (figs. 21 and 22; Bigsby and Sollid, 1975; Durst, 1981). In the area studied by Bigsby and Sollid, the lower bed, X, is 0.3–1.2 m thick, with an average thickness of 0.79 m. The upper bed, Y, is 0.46–1.1 m thick, with an average thickness of 0.71 m. The lower bed is 3.7–5.5 m below the upper bed, with an average separation of 4.3 m. Both beds are thicker than the 0.6-m minimum limit that is usually considered minable (Bigsby and Sollid, 1975). The average overburden thickness for the evaluated claims is 6 m on the upper bed and 8.5 m on the lower bed. Stripping ratios are generally less than 10:1. In the area examined by Durst (1981), the upper bed, is typically 0.3–0.6 m thick, and the lower bed is 0.76–1.2 m thick. The layers are separated by approximately 3 m of bentonite-rich shale. Furthermore, a third, orange bentonite bed, which is a few centimeters thick, is 6–15 m below the lower bed (Durst, 1981).

The upper and lower beds in the Malta area (Bigsby and Sollid, 1975; Durst, 1981) can be distinguished by the presence or absence of biotite grains and calcareous-clay concentrations. Numerous biotite grains are scattered through the lower bed, giving it a speckled appearance. The upper bed is characterized by the presence of calcareous-clay concretions. The concretions are white-colored cementations of the bentonite that appear to have grown in the bed, starting at the base and spreading upwards and outwards in a mushroom shape. Where the upper bed has been removed by erosion and the basal bedding plane of the upper bed is exposed, the concentrations appear in outcrop and on satellite imagery as circular white areas as great as 6 m in diameter (fig.22).

Two prominent bentonite beds also occur in the Glasgow area (figs. 21, 23). The lower and upper beds are 0.58–0.73 m and 0.63–0.79 m thick, respectively (David Crouse, Imerys, written commun., 2016). The upper bed is about 3.5–4.7 m below the lower bed. Biotite is present in the lower bed and calcareous concretions occur in the upper bed, just as in the Malta area.

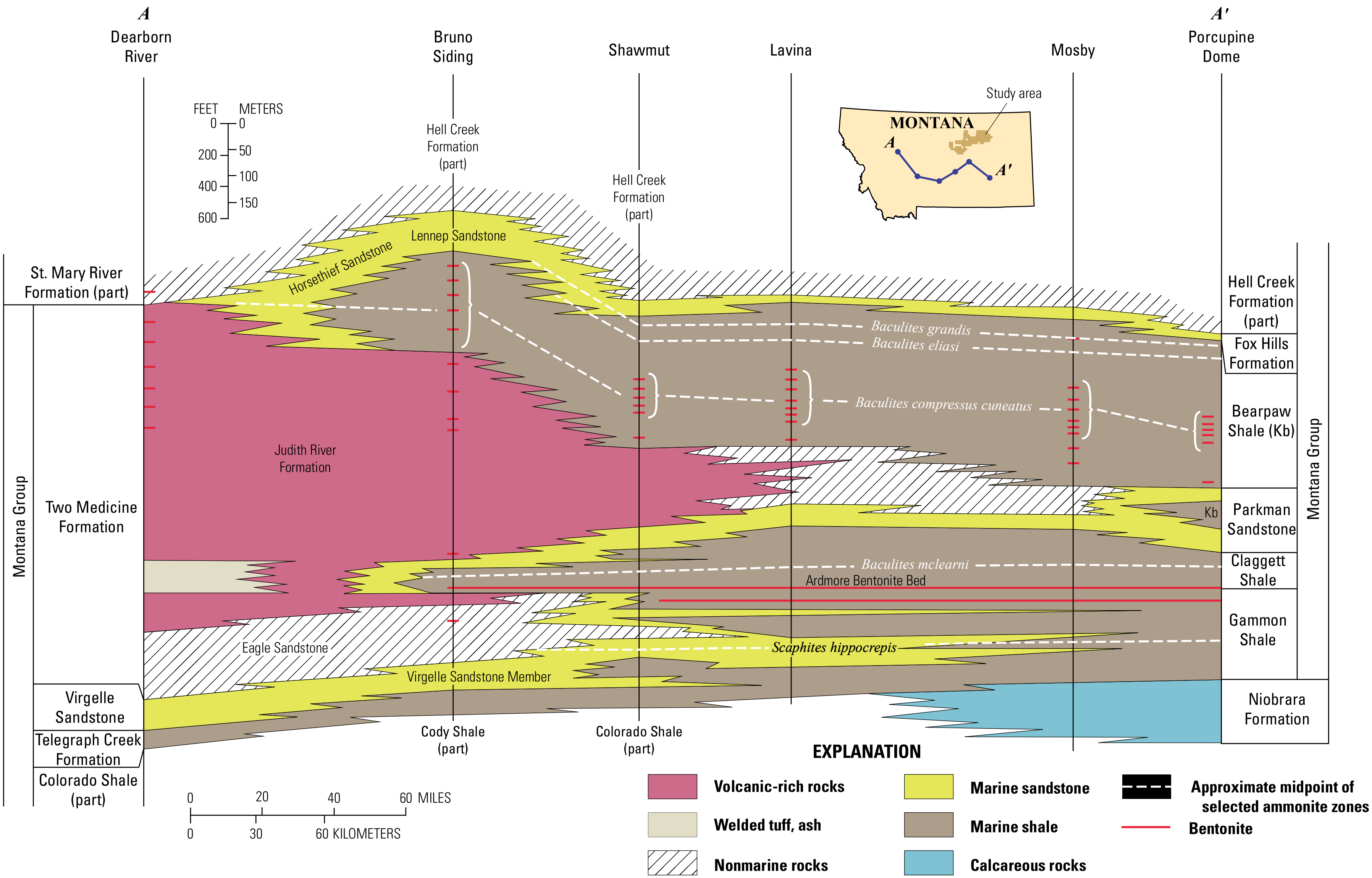


Figure 19. Schematic cross section showing the geology of the Montana Group from northwest to southeast Montana (*A*–*A*′). Prominent bentonite beds occur in the Gammon Shale and Claggett Shale in the lower part of the group and in the Bearpaw Shale in the upper part. Modified from Gill and Cobban (1973).

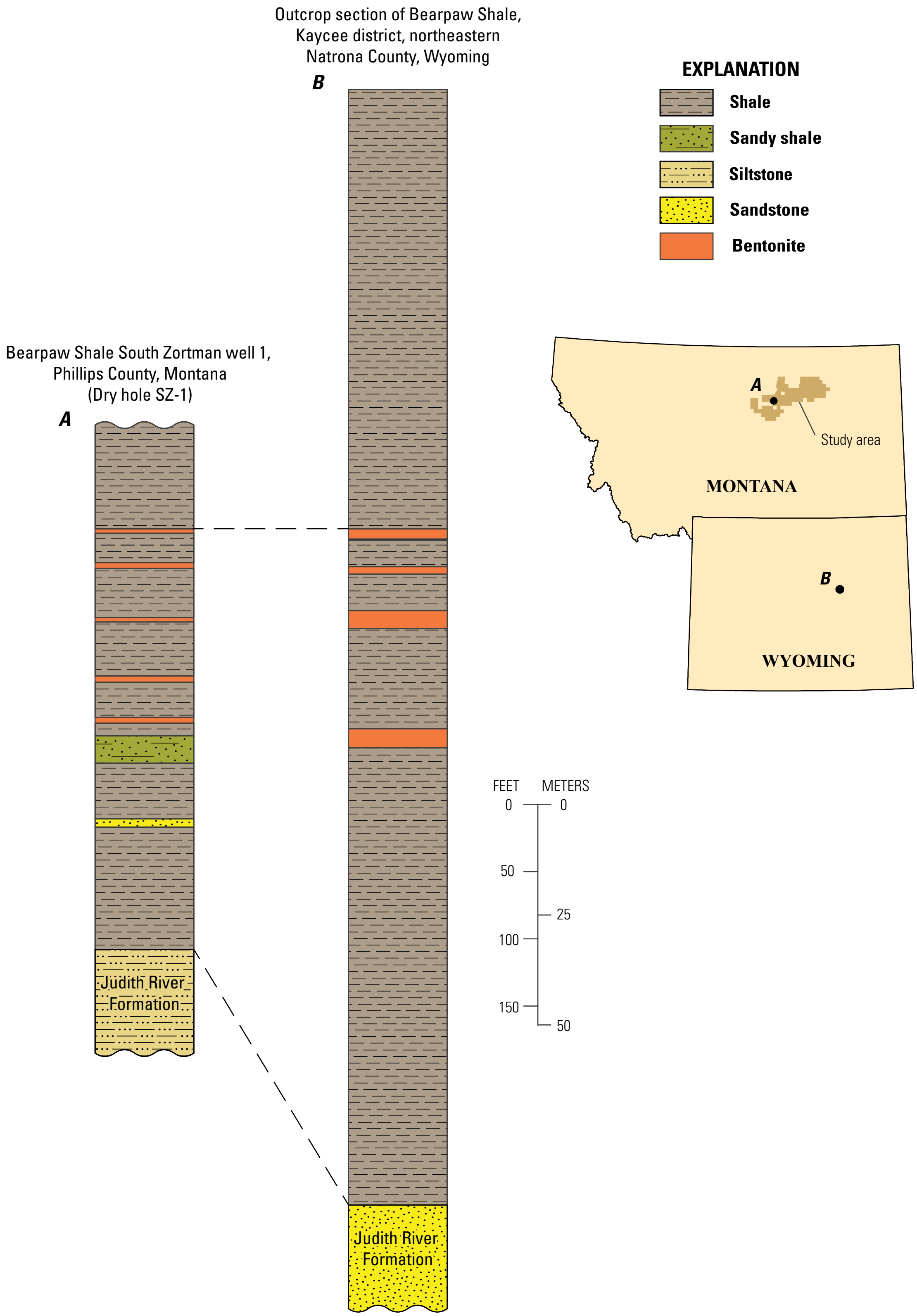


Figure 20. Stratigraphic columns showing bentonitic intervals in the Bearpaw Shale, Montana and Wyoming. *A*, Stratigraphic column from Continental Oil Company's South Zortman well 1 (dry hole SZ-1), Phillips County, Montana. Modified from Knechtel (1959). *B*, Stratigraphic column from an outcrop section, Kaycee District, Natrona County, Wyoming. Modified from Merewether (1996, figure 19).

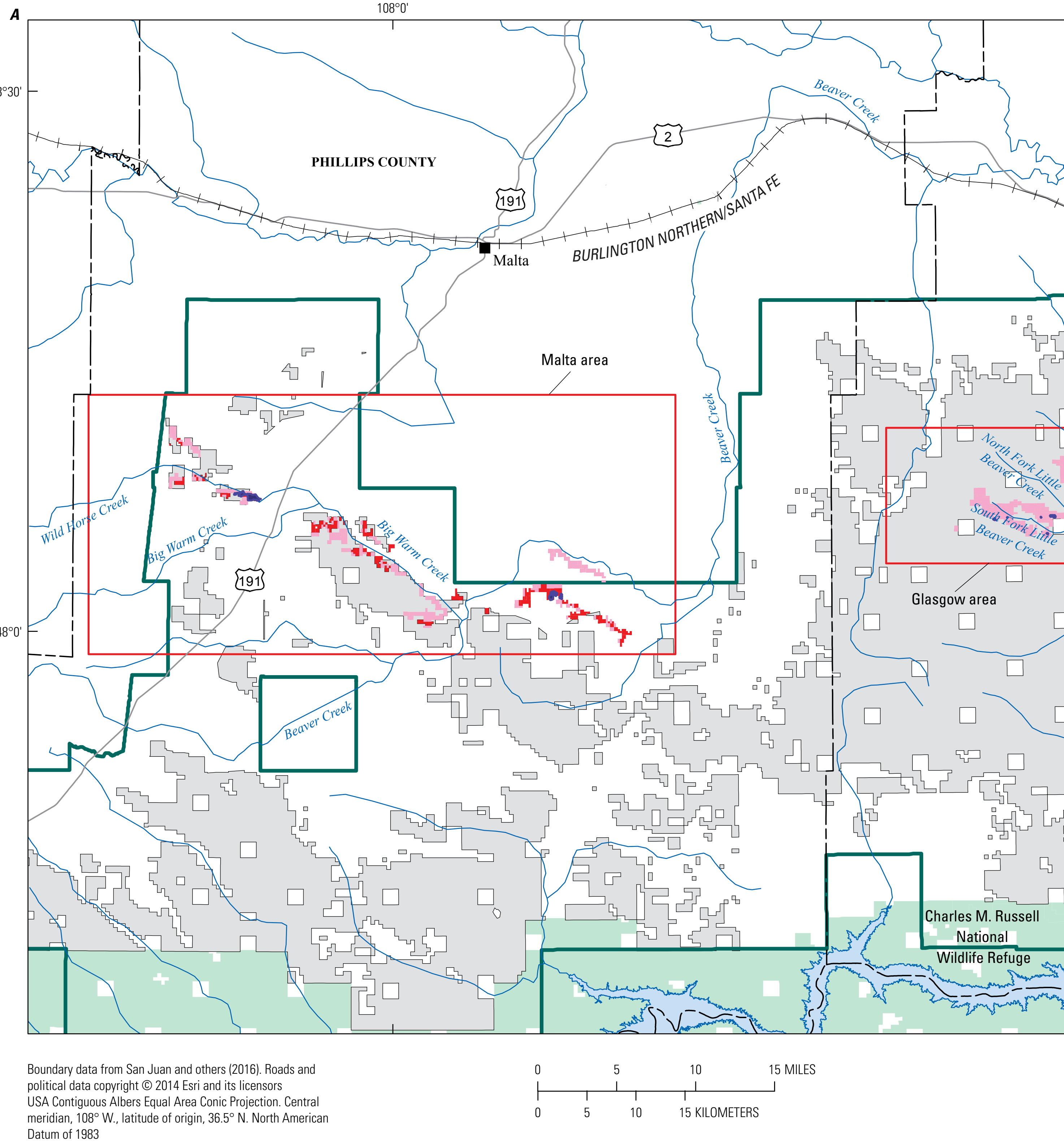
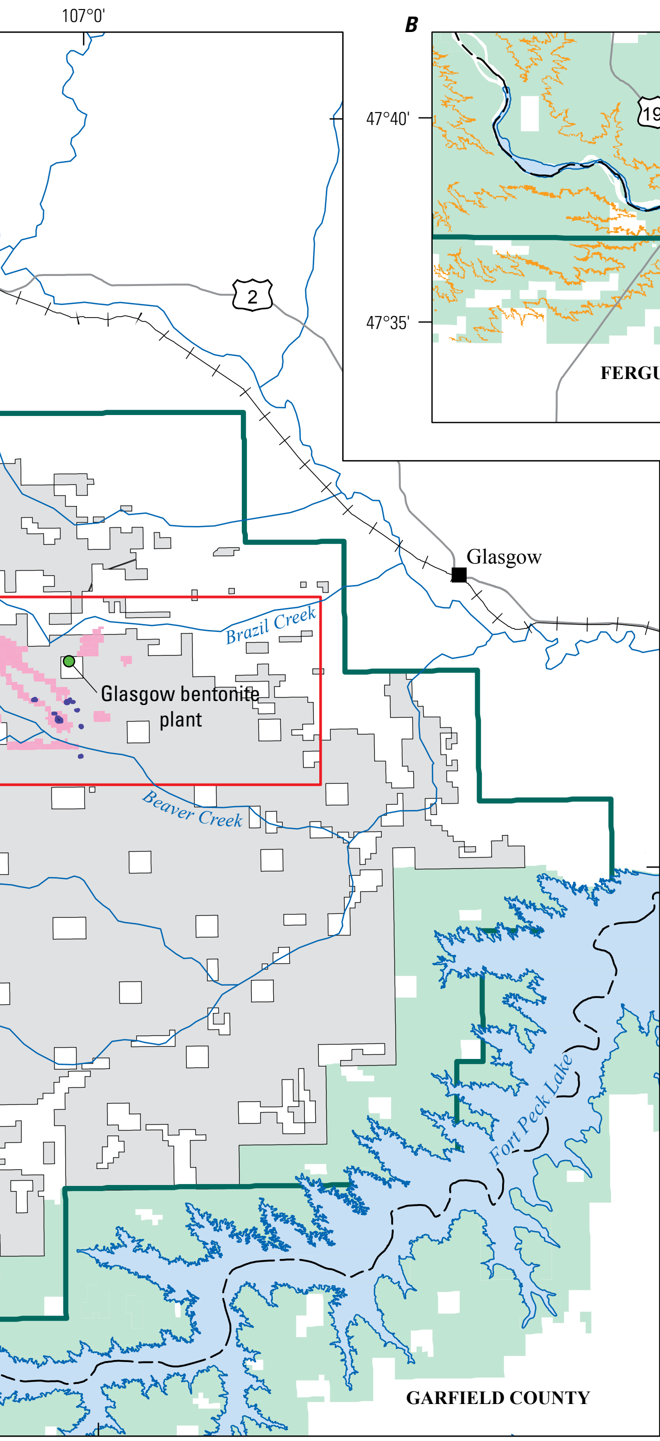


Figure 21. Map showing the location of bentonite occurrences in the Bearpaw Shale in the North-Central Montana Sagebrush Focal Area. *A*, Patented and placer claims located for bentonite resources in the Malta and Glasgow areas, Montana. Most of the bentonite exploration and development activity in the North-Central Montana Sagebrush Focal Area has been concentrated in these two regions. Claim data compiled from records provided by Nathanial Arave, Bureau of Land Management, Billings, Montana. *B*, Outcrop distribution of the Siparyann bentonite bed in the western part of the Charles M. Russell National Wildlife Refuge. Modified from Miller and others (1979). USGS, U.S. Geological Survey.



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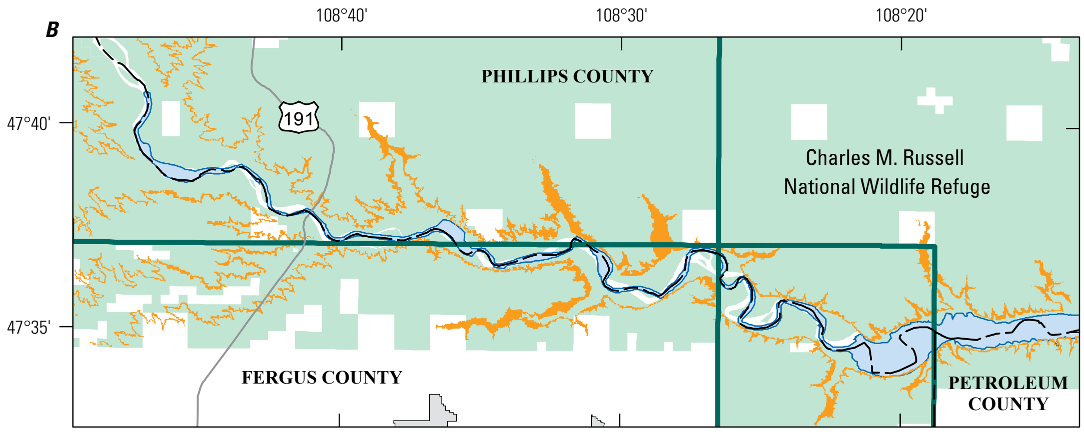
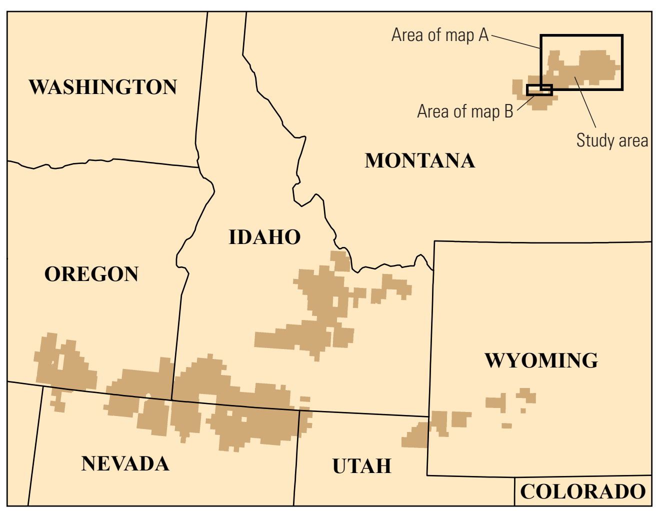


EXPLANATION

- USGS study area boundary
- Proposed withdrawal area
- Siparyann bentonite bed
- Placer claim located for bentonite
- Patented placer claim
- Area with bentonite resource
- Mined out bentonite pit
- Charles M. Russell National Wildlife Refuge



A

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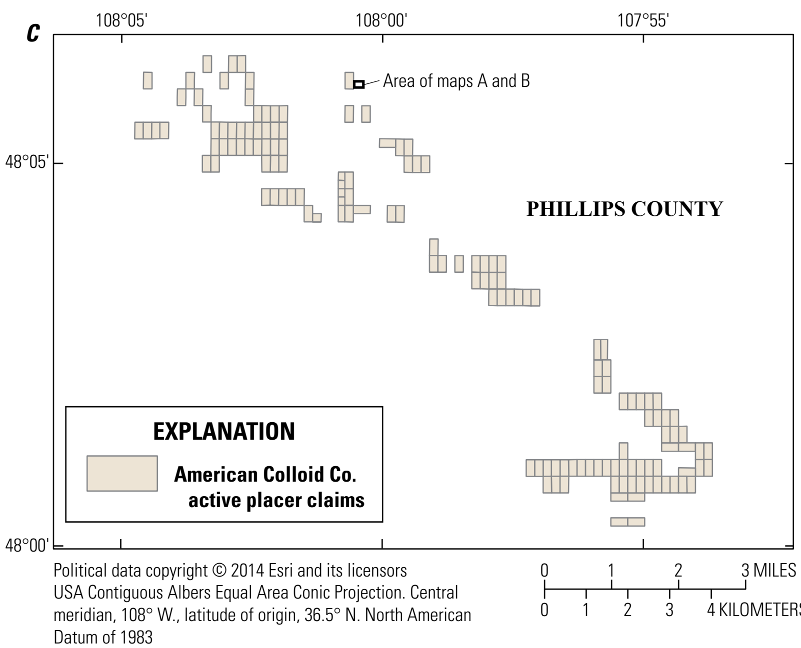
C



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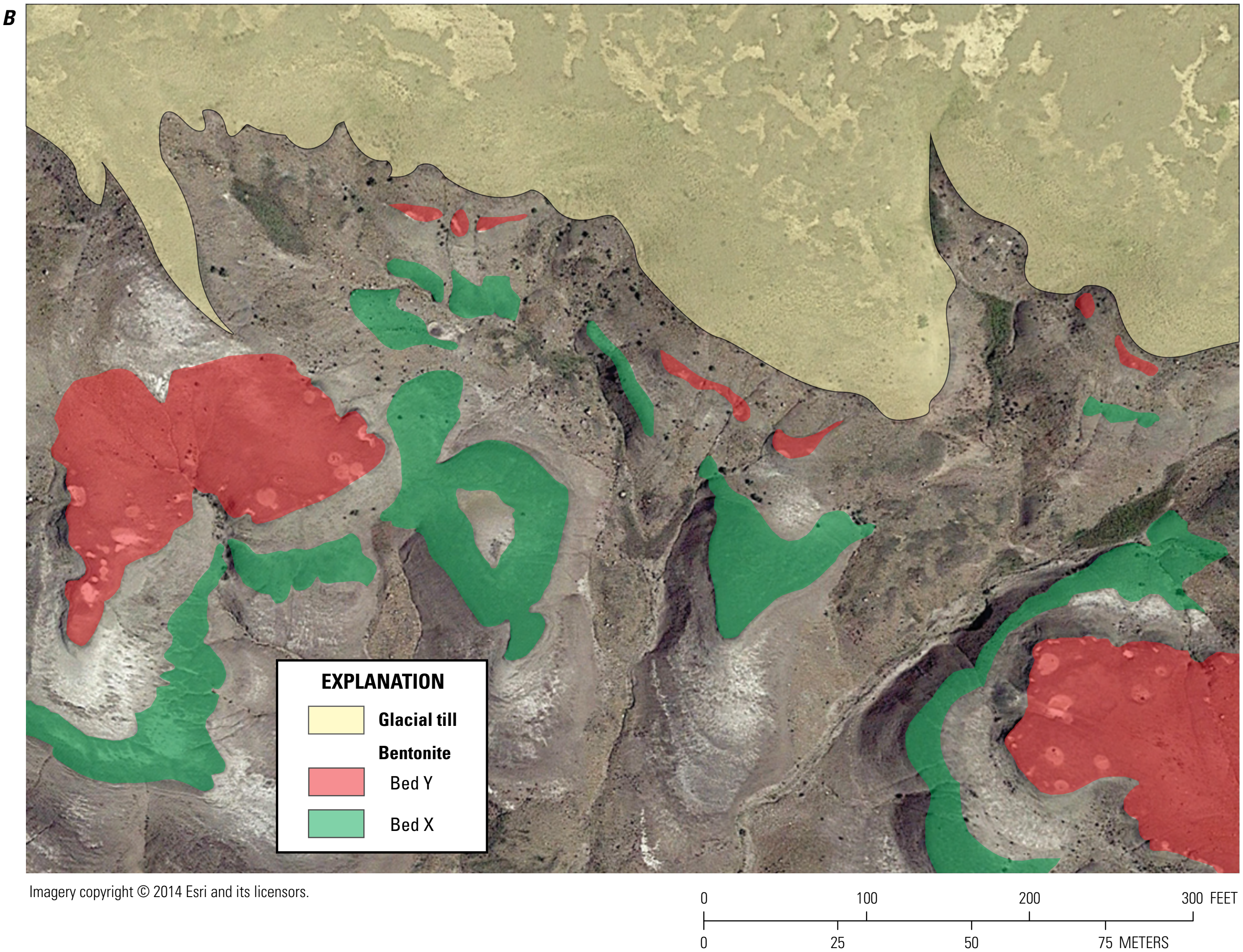
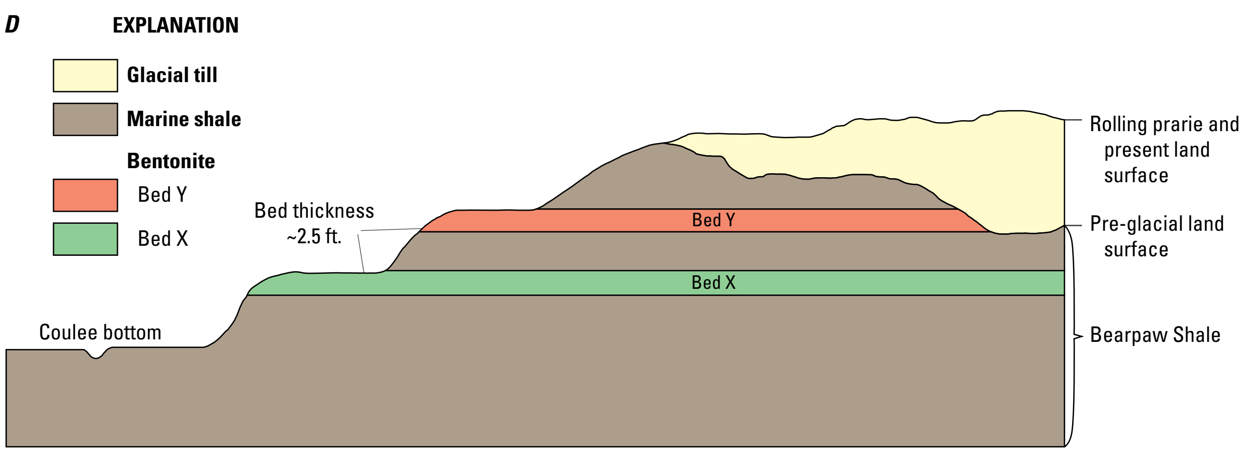
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 22. Imagery, bentonite geology, and claims in the Malta area, Montana. *A*, Satellite image. *B*, Interpretations of areas underlain by glacial till and the X and Y bentonite beds. Circular white features in the areas underlain by the Y bentonite bed are calcareous concretions. *C*, Index map showing location of the image in relation to American Colloid Co. placer





mining claims located for bentonite. Claim data compiled from records provided by Nathanial Arave, Bureau of Land Management, Billings, Montana. *D*, Schematic cross section showing relation of landforms developed on geologic and surficial units in the Malta area. Modified from Bigsby and Sollid (1975).

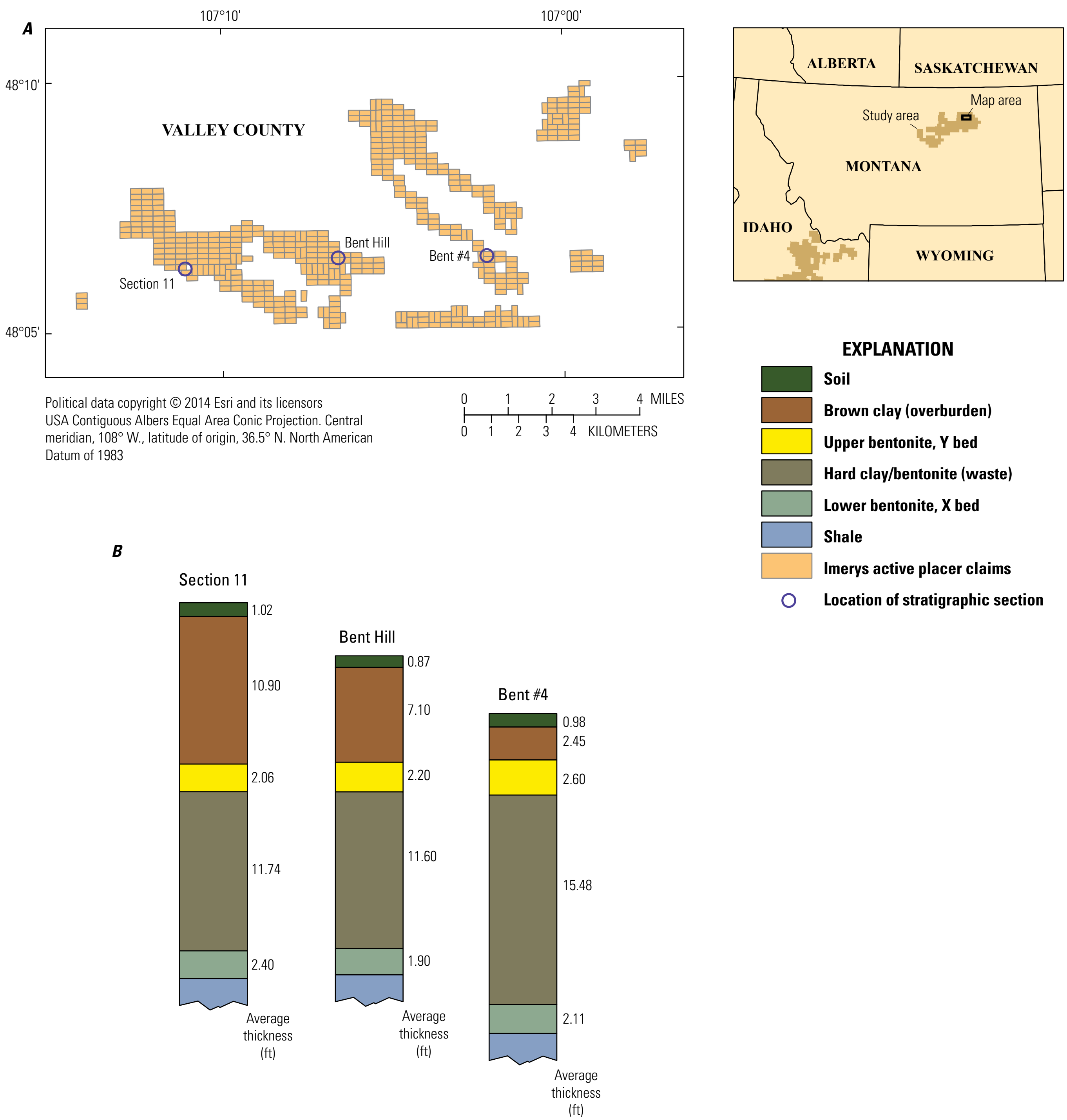


Figure 23. Generalized stratigraphy of bentonite beds in the Glasgow area, Montana. *A*, Map showing location of stratigraphic columns in relation to active placer claims located for bentonite. *B*, Stratigraphic columns showing thickness and stratigraphic separation of the lower and upper bentonite layers. Map and sections modified from David Crouse, Imerys, written commun., April 2016.

Hosterman and Patterson (1992) correlate these two beds in the bentonite-rich interval in the Bearpaw Shale in the Malta and Glasgow areas (fig. 21) to the X and Y beds in the Ingomar-Vananda area in south-central Montana (fig. 17; Berg, 1970). Throughout this report, the upper bed in the Malta and Glasgow areas is referred to as "X", and the lower bed as "Y". In the Ingomar-Vananda area, Berg (1970) describes two bentonite beds that are 0.9–1.2 m thick, and are separated by approximately 3 m of montmorillonite-rich shale. The lower of the two beds (X bed) is 90–120 cm thick, pale-olive color on a fresh moist surface, light gray on a dry surface, and contains flakes of biotite that are visible in hand samples. The upper bed (Y bed) is 76–107 cm thick, greenish yellow, and does not contain visible biotite phenocrysts in hand samples. The most characteristic feature of the Y bed is buff-colored calcareous concretions composed of calcite and montmorillonite. The concretions are generally ovoid and range from 0.3 to 5.5 m in diameter. The concretions are concentrated at the base of the bentonite bed, and in some places, form a continuous layer several centimeters thick. Similarities in the thickness of the beds and their stratigraphic separation, association of biotite with the lower bed, and concentrations within the upper bed support the interpreted correlation.

In the Hardin District (figs. 17, 18), Knechtel and Patterson (1956) describe beds V, W, and X but do not describe a Y bentonite bed. The bentonite beds are notably thicker in this district than in the Ingomar-Vananda and Malta-Glasgow areas. The V bed is as much as 6.8 m thick; calcareous concretions 2.4–3.6 m in diameter are abundant on the exposed surfaces of this bed. The W bed consists of 0.9–2.4 m of light-colored bentonite. The X bed is as much as 2.1 m thick and locally contains large, gray, calcareous concentrations.

Exploration and Mining Activity

Bentonite exploration and mining activity has been ongoing in the Malta and Glasgow areas for at least 60 years (table 7). The locations of active placer claims and mineral patents are shown on figure 21. The spatial database of active placer claims[1] located for bentonite was derived from records provided by the BLM office in Billings, Montana. A spatial database showing the location of mineral patents for bentonite was derived from records provided by the BLM office in Billings and a Web page for General Land Office records (Bureau of Land Management, 2016a). Using mineral occurrence and permit databases, we located 21 open pits that were previously mined for bentonite, and we created a database from spatially referenced satellite imagery (figs. 13, 21; table 8).

Bentonite was discovered in the Glasgow area in 1955; we could not find information regarding when bentonite was found in the Malta area. There is almost no information on the exploration activity that occurred between discovery and when mining first took place in 1976 (Glasgow) and 1978 (Malta). Mapping, drilling, and sampling programs must have been conducted but this information is not publicly available. Based on their exploration work, American Colloid submitted applications and received patents on more than 200 placer claims between 1978 and 1984 that cover about 15.7 km^2 (Bureau of Land Management, 2016a).

Mining continued until about 1986, at which time American Colloid had processed approximately 0.91 million metric tons (Mt) of bentonite from their plant in Malta. Federal Bentonite processed less than 0.91 Mt of bentonite at their plant near Glasgow and shipped another 163,000 metric tons of bulk material by rail. Federal Bentonite produced 838,000 metric tons between 1978 and 1986 (Gregg Menge, oral commun., 2016). Bentonite was extracted from at least 21 open-pit mines in the Malta and Glasgow areas. A rail spur linked the plant near Glasgow to the Burlington Northern-Santa Fe railroad that runs across northern Montana.

Following closure of the mines near Glasgow in about 1986, the Brazil Creek Bentonite Company and its affiliates dropped all their placer bentonite claims in the Glasgow area. The area was staked again by Gregg Menge of Lewistown, Montana beginning in the early 1990s. As of 2016, there are 450 active bentonite placer claims in the Glasgow area that cover approximately 36 km^2. A plan of operations to produce bentonite on the Bent Number 4 claim was submitted to the BLM in 2015 and approved in 2016. The claims in the Glasgow area are currently held by Imerys, a company specializing in the production and processing of industrial minerals (David Crouse, Imerys, written commun., April 2016).

After the plant at Malta was closed and demolished, placer claims appear to have been dropped and re-acquired at least twice. As of 2016, American Colloid Company has 320 active bentonite claims in the Malta area that cover about 25 km^2. No recent applications have been submitted to the BLM under 43 CFR 3809.

For the Malta area, mineral-resource estimates must have been calculated as part of the mineral patent and validity examination process. Only two BLM mineral reports covering 76 claims were available for this study. American Colloid Company estimated 3.1 Mt bentonite for the upper and lower beds in one group of 38 claims that cover 2.9 km^2 (Bigsby and Sollid, 1975). The tonnages were calculated on a dry basis using 1.6 metric tons dry bentonite per cubic meter of in-place material. For a separate group of 38 placer claims, the tonnage estimate provided by American Colloid was 1.03 Mt for an unspecified acreage (Durst, 1981). Tonnage was calculated using approximate bulk density of 1.6 metric tons dry bentonite per cubic meter (Durst, 1981). The report by Durst (1981) also provides a "reserve" statement from American Colloid at the time the report was prepared. They estimated 25.2 Mt in the field, which corresponds to 18.8 Mt of processed bentonite (table 9).

[1]Under the 1872 Mining Law, placer claims originally included only deposits of mineral-bearing sand and gravel containing free gold or other detrital minerals. By congressional acts and judicial interpretations, many nonmetallic bedded or layered deposits, such as gypsum and bentonite, are also located as placer claims (Bureau of Land Management, 2011).

Table 7. Summary of bentonite-related exploration and mining activities in the North-Central Montana Sagebrush Focal Area.

[TCM, Tax Court Memorandum; IBLA, Interior Board of Land Appeals; Mt, million metric ton]

Date	Text	Reference
1955	Robert Hansen discovered an unknown amount of bentonite on public lands in 1955.	Hansen v. Commissioner (34 TCM 1488 [1975])
1958	The Brazil Creek Bentonite Company was formed to mine the bentonite discovered near Brazil Creek, southwest of Glasgow. The company staked 100 mining claims.	Hansen v. Commissioner (34 TCM 1488 [1975])
1965	Brazil Creek Bentonite Company granted Archer-Daniels-Midland Company an option to purchase the bentonite on its claims. Subsequently, Ashland Oil and Refining Company acquired all interests of Archer-Daniels-Midland. Federal Bentonite, in turn, acquired all the interests of Ashland.	Hansen v. Commissioner (34 TCM 1488 [1975])
1976	Federal Bentonite, a division of Aurora Industries, Aurora Illinois, opened a small bentonite processing plant southeast of Glasgow. The bentonite claims were leased from Brazil Creek Mining Company.	Bureau of Land Management (1980)
1976	Surface-management regulations (43 CFR 3809) were published as a proposed rulemaking.	Bureau of Land Management (1980, 2000)
1978	American Colloid Company opened a bentonite processing plant in Malta, Montana.	Pederson (2004); Bureau of Land Management (1980)
1978 to 1984	American Colloid patented 209 mining claims.	Bureau of Land Management (2016a)
1979	Federal Bentonite processing plant closed after processing less than 0.91 Mt tons of bentonite.	Bureau of Land Management (2015a); Bureau of Land Management (1992)
1982	Lawsuit clarified status of bentonite as locatable mineral.	United States v. Kaycee Bentonite Corp. (64 IBLA 183, 233 [1982])
1983 to 1985	After the Malta plant closed, Federal Bentonite mined, solar dried, and shipped in bulk by rail approximately 163,000 metric tons of bentonite.	Bureau of Land Management (1992)
1986	American Colloid closed and demolished the Malta plant after processing approximately 0.91 Mt tons of bentonite.	Bureau of Land Management (1980); Pederson (2004)
1988	The 228 unpatented claims located for bentonite in the Brazil Creek area were abandoned.	Bureau of Land Management (1992); Causey (2011)
1993	Annual maintenance fee required for unpatented mining claims.	30 U.S.C. 28f - Fee
1993	Placer claims in the Malta area abandoned.	Causey (2011)
1993–2007	Bentonite claims re-staked in the Brazil Creek area by Gregg Menge.	Causey (2011); Gregg Menge, oral commun., March 2016.
1994 to 1995	Moratorium on patent applications.	Bureau of Land Management (2010)
2005	The Montana Department of Revenue enacted the Bentonite Production and Royalty Tax on the gross yield of bentonite produced replacing the tax on mines net proceeds similar to other miscellaneous minerals.	Montana Tax Foundation Inc. (2007); Montana Department of Revenue (2014); Montana Legislative Services (2015)
2006	Placer claims in the Malta area re-staked.	Causey (2011)
2008 and 2009	The global recession and corresponding cuts in steel production caused a drop in price and reduced demand for bentonite.	Virta (2010)
2010	Placer claims in the Malta area abandoned.	Causey (2011)
2013	American Colloid recorded placer claims in the Malta area.	Recordation receipts in BLM office, Billing, Montana.
2014	S and B Industrial Minerals North America submitted opencut mining plan of operations for Bent Hill to the State of Montana	Montana Department of Environmental Quality (2016)
2015	S and B Industrial Minerals North America submitted a plan of operations to the BLM for Bentonite #4 site.	Bureau of Land Management (2015a)
2015	Imerys, a French multinational company which specializes in the production and processing of industrial minerals acquired S and B Minerals.	Imerys (2015)
2016	Plan of operations to mine bentonite at the Bentonite #4 site approved.	KLTZ (2015)

Table 8. Bentonite pit locations in and near the North-Central Montana Sagebrush Focal Area.

[BLM, Bureau of Land Management; ND, no data; PWA, proposed withdrawal area; T, township; R, range; S, section]

Surface-management agency or owner	Deposit name	Claim name	Claimant	Proposed withdrawal area (PWA)	Latitude (decimal degrees)	Longitude (decimal degrees)	Township-Range Sections	Aliquot
Private land	ND	ND	ND	Farther than 500 m from PWA	47.3706	108.7823	T19N R23E S33	NWNW
Private land	ND	ND	ND	Farther than 500 m from PWA	47.3716	108.7836	T19N R23E S33	NENE
Federal (BLM)	Bentonite Number 6 Mine	ND	ND	Completely within PWA	48.0791	107.0102	T27N R36.5E S24	L5
Federal (BLM)	Bentonite Number 5 Mine	P46	Imerys	Completely within PWA	48.0885	107.1116	T27N R36E S17	SWSE
Federal (BLM) and private land	ND	PAUL25, PAUL26	American Colloid Co.	Within 500 m of PWA	48.0328	107.7719	T26N R31E S06	SESE, SENESE
Federal (BLM)	Bentonite Number 4 Mine	ND	ND	Completely within PWA	48.0991	107.0094	T27N R36.5E S13	L1
Private land	ND	ND	ND	Within 500 m from PWA	48.0340	107.7837	T26N R31E S06	NESW, SWSW, SESW, SESENW, NWNWSE, NENWSE, SWNWSE, SENWSE
Federal (BLM)	ND	ND	ND	Completely within PWA	48.1038	107.0313	T27N R36E S12	SESW
Federal (BLM)	ND	B4	Imerys	Completely within PWA	48.1079	107.0356	T27N R36E S12	NWSW
Federal (BLM)	Bentonite Number 3 Mine	ND	ND	Completely within PWA	48.1103	107.0120	T27N R36.5E S12	L4
Federal (BLM)	Bentonite Number 3 Mine	ND	ND	Completely within PWA	48.1110	107.0134	T27N R36.5E S12	L3
Federal (BLM)	ND	P61, B19	Imerys	Completely within PWA	48.1036	107.1202	T27N R36E S08	SESW, SWSW
Federal (BLM)	ND	R95, R373, R374	Imerys	Completely within PWA	48.1046	107.1039	T27N R36E S08; T27 R36E S09	SESE; SWSW
Federal (BLM)	ND	R78	Imerys	Completely within PWA	48.1039	107.1659	T27N R35E S12	SWSW
Federal (BLM)	ND	ND	ND	Completely within PWA	48.1156	107.0176	T27N R36E S12; T27N R36.5E S12	NENE; L2
Federal (BLM)	Bentonite Number 1 Mine	B43, R75	Imerys	Completely within PWA	48.1022	107.1834	T27N R35E S11; T27N R35E S14	SWSW, SESW; NWNW, NENW

Table 8. Bentonite pit locations in and near the North-Central Montana Sagebrush Focal Area.—Continued

[BLM, Bureau of Land Management; ND, no data; PWA, proposed withdrawal area; T, township; R, range; S, section]

Surface-management agency or owner	Deposit name	Claim name	Claimant	Proposed withdrawal area (PWA)	Latitude (decimal degrees)	Longitude (decimal degrees)	Township-Range Sections	Aliquot
Federal (BLM)	ND	R121, R120	Imerys	Completely within PWA	48.1159	107.0223	T27N R36E S01; T27N R36E S12	SWSE, SESE; NWNE, NENE
Federal (BLM)	ND	R109, R107	Imerys	Completely within PWA	48.1173	107.0549	T27N R36E S20	SWSW, SESW
Federal (BLM) and private land	ND	LEK 74, LEK73	American Colloid Co.	Within 500 m of PWA	48.1246	108.1904	T27N R27E S02; T27N R27E S01	NESENE, SESENE; NWSWNW, NESWNW, SWSWNW, SESWNW, NWSW, SENW, NWNESW, NENESW, SWNESW, SENESW, SWNE, NWSE
Federal (BLM)	ND	ND	ND	Completely within PWA	48.1278	108.2140	T27N R27E S02	SWNW, SENW
Federal (BLM) and private land	ND	LEK 68, LEK69	American Colloid Co.	Within 500 m of PWA	48.1278	108.2055	T27N R27E S02	NENW, SENW, NWNE, SWNE, NWSENE

Table 9. "Reserves" stated by American Colloid Company in 1981 for properties in the Malta area, Montana (Durst, 1981).

[Reserves are in quotes because it is unknown if the tonnages solely represent that part of the mineral inventory that is economic. Processing 1.34 metric tons (Mt) of bentonite in the field yields a metric ton of processed bentonite]

Land type	Bentonite in the field (Mt)	Processed bentonite (Mt)
Unpatented claims	17	12.7
Private land	3.92	2.92
Private lease	4.13	3.08
State lease	0.181	0.135
Total	25.2	18.8

Calculating tonnage for flat-lying beds of bentonite is fairly straightforward—it is the product of the area of the unit, its thickness, and the bulk density of the ore material (volume × bulk density). The only complication is the effect of moisture content on the bulk density used for bentonite. Calculated tonnage of bentonite in the Malta area assumed an original moisture content of 31 percent (2.1 metric tons per cubic meter), a reduced moisture content of 13 percent (1.83 metric tons per cubic meter), and 90 percent recovery:

$$\text{Calculated tonnage} = (1.647 \text{ metric tons}) \times (\text{area } [m^2]) \times (\text{average bed thickness } [m]) \text{ (Durst, 1981).}$$

Potential for Occurrence

There are no known maps that show the distribution of bentonite-rich intervals in the middle part of the Bearpaw Shale or the important bentonite beds, X and Y, in the Malta-Glasgow area. There are maps that show the Siparyann bed in the Charles M. Russell National Wildlife Refuge, which are appropriate for the scale of this assessment. For this report, geologic models were developed to estimate the distribution of the bentonite-bearing rocks. When considering mineral potential, we focused on identifying areas where thick (~0.6 m) bentonite beds could be mined using open-pit methods with relatively low stripping ratios (~10:1 or less).

Nine bentonite tracts, MTB01 to MTB09, were delineated (appendix 2; San Juan and others, 2016). The lower X and upper Y bentonite beds in the Glasgow and Malta areas were assessed in detail (figs. 24 and 25). Outside these two areas, we completed a generalized evaluation of the bentonitic interval in the Bearpaw Shale and bentonite beds in the Fox Hills and Hell Creek Formations in the rest of the study area (fig. 26). For the final mineral potential map and GIS, the detailed and generalized assessments were integrated (fig. 27). Generalized results were removed from the areas where the X and Y beds in the Bearpaw Shale in the Malta and Glasgow areas were studied in detail (fig. 26) and the detailed assessment results shown in figures 24 and 25 were inserted. The final potential results included in the GIS database (San Juan and others, 2016) are shown in figure 27. The following sections describe the assessment process for the various areas.

Geostatistical Modeling of the X and Y Beds in the Bearpaw Shale, Malta and Glasgow areas: Tracts MTB06 to MTB09

For the Malta and Glasgow areas, predictive models based on the distribution of concretions associated with the Y bentonite bed were created to estimate where the X and Y bentonite beds are exposed, or under less than 3.6 m of cover. The concretions form bright, gray to white, circular features as great as 6 m in diameter on exposed bedding planes (fig. 22). Using GIS software, a geologist digitized the distribution of concretions, as seen on the satellite images, as short line segments. Each line segment represents one or more concretions along the base of the Y bed. The line file segments were converted to points and an elevation for each point was extracted from a 30-m digital elevation model. The distribution of concretions mapped by geologists using GIS software gives a quick overview of where bentonite beds are present and the point information was used to create a geostatistical model of the lower contact of the Y bed, as described below.

Using the point data for the distribution of Y-bed concretions as input for empirical Bayesian kriging, geostatistical models (prediction surface and error map) for the base of the Y bed were created separately for the Malta and Glasgow areas. Model parameters are summarized in appendix 4. The geostatistical models, which represent the lower contact of the Y bed, were converted to raster files, and then subtracted from the 30-m digital elevation model. On maps, the value of zero would approximate the location of the base of the Y bed where exposed at the surface. Results of the raster calculation were classified into two categories: (1) one that represents a typical elevation distance between the base of the upper and lower bentonite beds and (2) one that represents the Y bed and an amount of overburden consistent with a low strip ratio (3.6 m) (fig. 24). A map of the distribution of the two model categories shows a close relation to the distribution of patented and active placer claims for bentonite in the two areas. This is to be expected if the model is successful. Error maps show best results near observation points used to construct the geostatistical model (fig. 25). In addition to predicting what we know, the model shows that the two bentonite beds should extend well beyond the current distribution of mining claims. In the Malta area, the model predicts about 158 km^2 where the X and Y beds are at or near the surface (about 24 km^2 in the proposed withdrawal area). In the Glasgow area, the model predicts about 120 km^2 where the X and Y beds are at or near the surface within the study area (about 100 km^2 in the proposed withdrawal area). By comparison, American Colloid has patented and active placer claims covering 41 km^2 in the Malta area, and Imerys has placer claims covering approximately 36 km^2 in the Glasgow area. Model results for the X and Y bentonite beds were converted to mineral potential tracts, clipped to the USGS study area boundary, and included in the mineral potential tracts database (MTB06 to MTB09, appendix 2; fig. 25; San Juan and others, 2016).

Occurrence of Bentonite Outside the Malta and Glasgow Areas

Bentonite is an important locatable mineral in the study area. Unfortunately, no detailed geologic maps exist in the public domain that define the distribution of bentonite beds. Therefore, we developed the following model to help provide a modern assessment.

For the study area outside the Malta and Glasgow area, a different strategy was used to delineate bentonite tracts because the bentonite beds and their associated concretions were harder to map on satellite images. For the bentonite-rich interval in the middle part of the Bearpaw Shale, a stratigraphic and geostatistical model was constructed to predict the outcrop extent. For bentonite in the Fox Hills and Hell Creek Formations, geologic map units were extracted from published 1:100,000-scale maps to show where bentonite could occur.

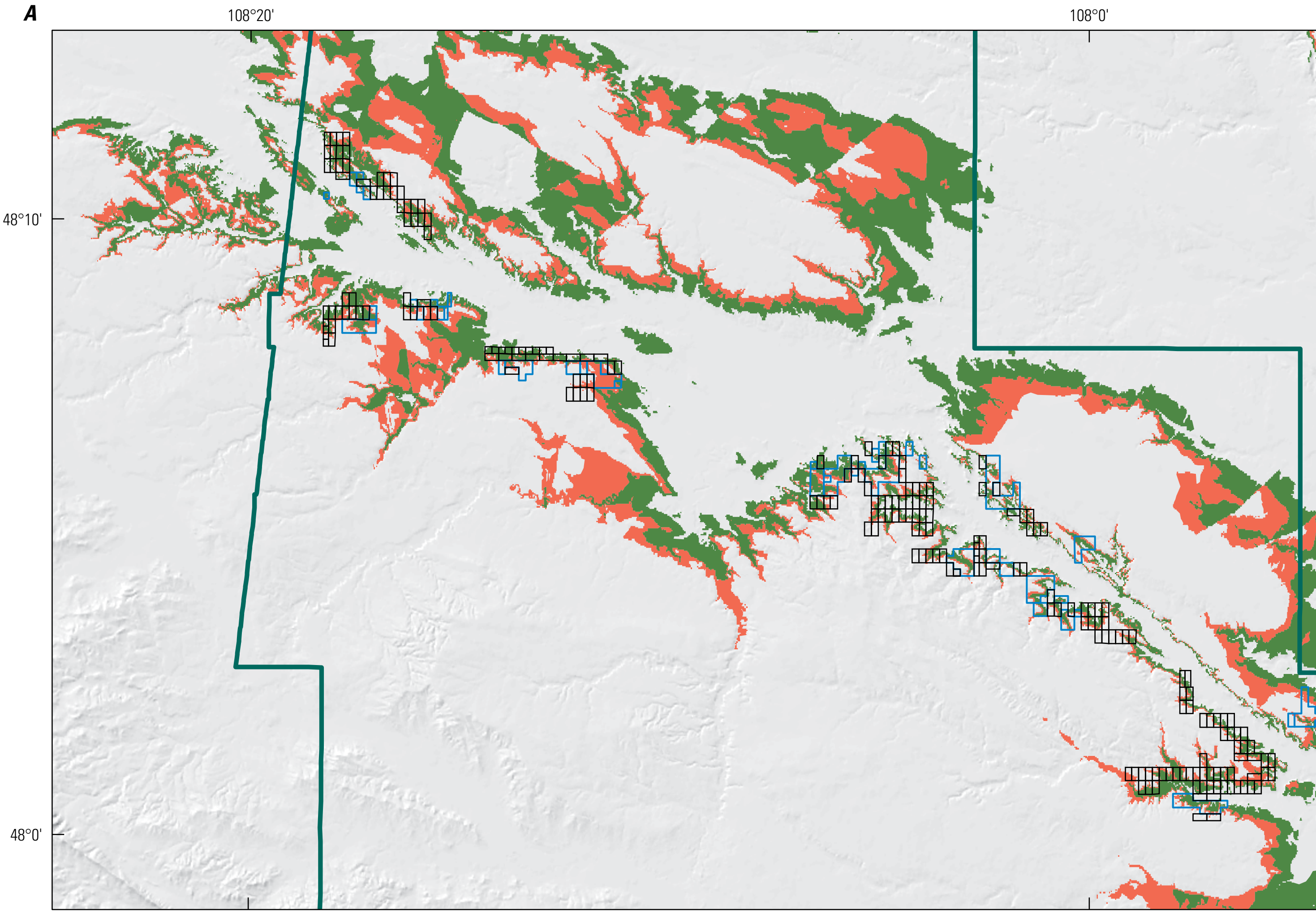
Stratigraphic and Facies Modeling to Map the Bentonitic Interval in the Bearpaw Shale: Tracts MTB01 to MTB03

A model was developed using stratigraphic information, interpolation, and raster mathematics to map the extent of the bentonite-rich interval that contains the X and Y bentonite beds in the Bearpaw Shale. The basic strategy was to use stratigraphic information in well data to create surfaces representing the upper and lower contacts of the bentonitic interval and to use GIS software to intersect these surfaces with the ground surface to show where they should crop out.

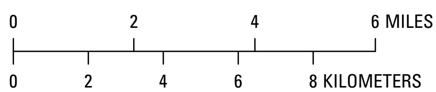
The bentonitic interval was not recorded in the logs for oil and gas wells that cut the Bearpaw Shale in the study area (Ronald M. Drake II, written commun., 2016), with the exception of Continental Oil Company's South Zortman well 1 (dry hole SZ-1; figs. 5, 20; plate 53 in Knechtel, 1959). The elevation of the top of the Judith River Formation was available in the wells, and was used to create a surface that represented that contact. Using the stratigraphic information in SZ-1, we added elevation to the Judith River Formation surface to create surfaces representing the bottom and top of the bentonite-rich interval as measured in dry hole SZ-1. The process for creating the surfaces is described below.

The elevation of the top of the Judith River Formation in oil and gas wells in and near the study area was derived from databases obtained from the Montana Board of Oil and Gas Conservation (2016). Formation tops were recorded as down-hole depths; elevations were calculated by subtracting the depth from the collar elevation of the well. About 1,500 drill holes intersected the top of the Judith River Formation in and near the study area. Most intersections were in oil and gas fields west, northwest, and north of the study area (fig. 10). Only 30 holes intersected the top of the Judith River Formation in the study area.

A



Base modified from U.S. Geological Survey DEM data, 2016. Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983



B

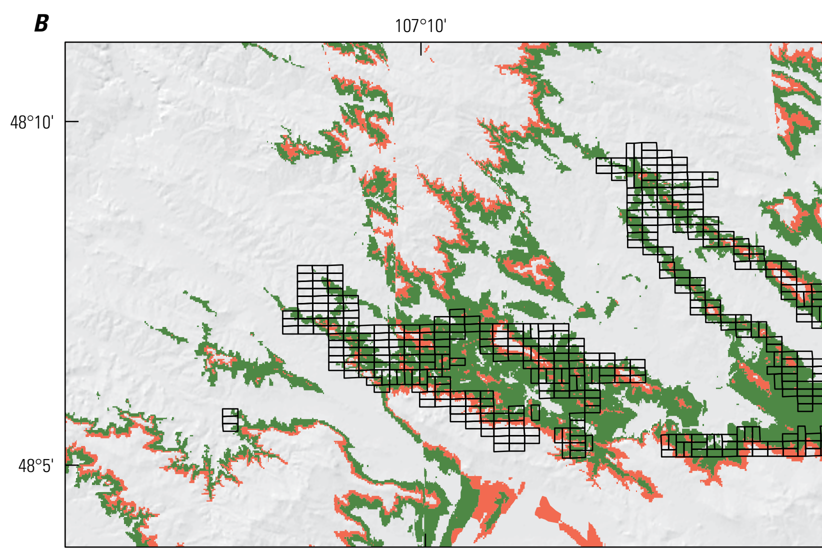
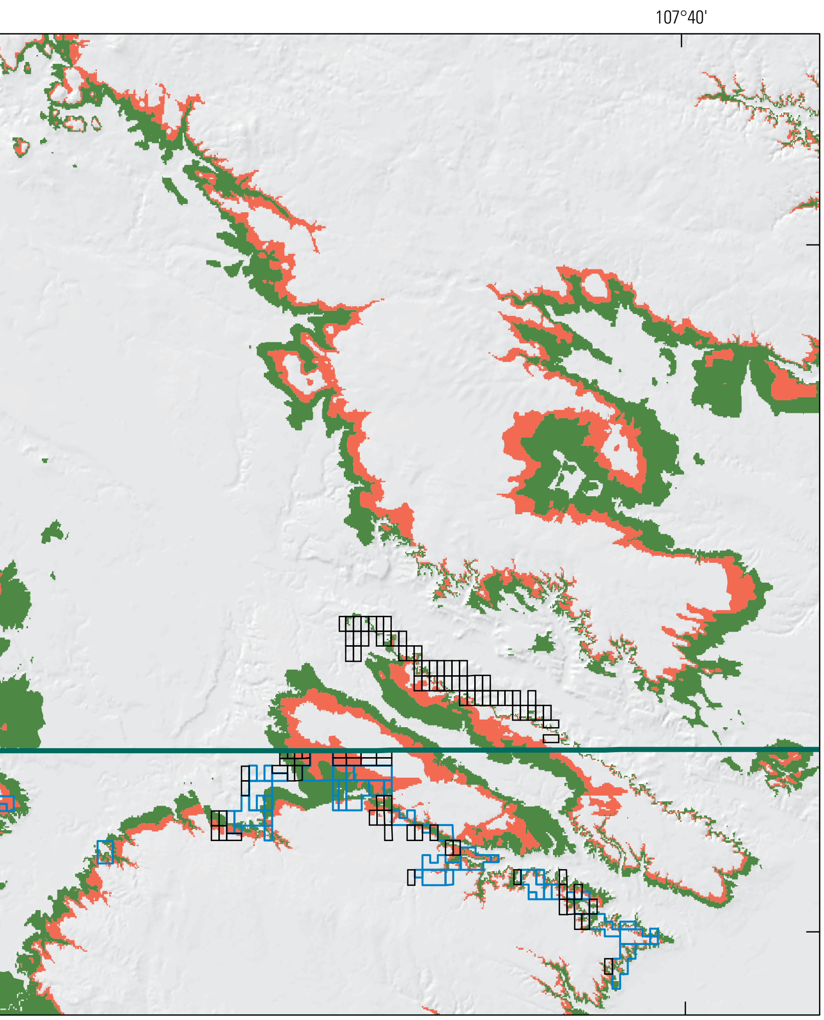
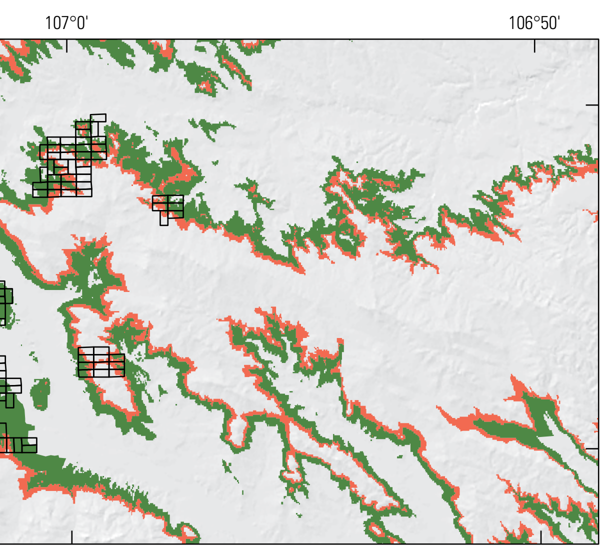


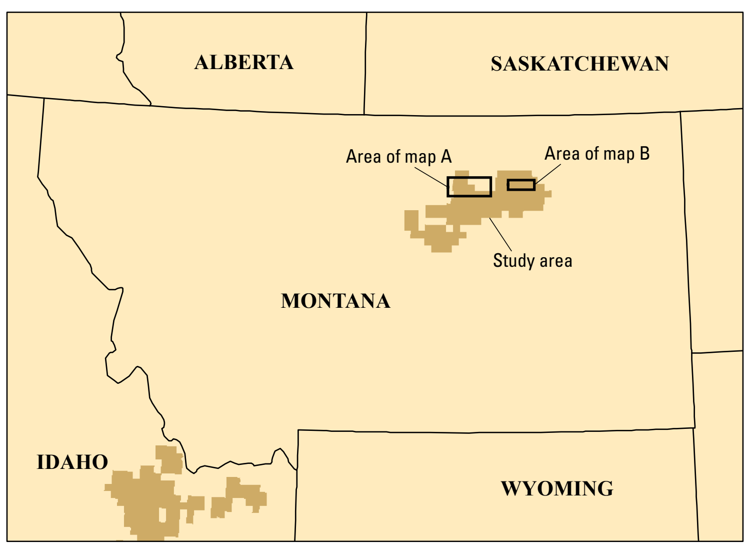
Figure 24. Maps showing predicted distribution of the X and Y bentonite beds in the Malta, *A*, and Glasgow, *B*, areas, Montana. Category –15 to 3 represents the area where the interval between the bottom of the X bed and the top of the Y bed could be exposed. Category 3.1 to 15 represents the area where the Y bed is overlain by less than 3.6 m of overburden. USGS, U.S. Geological Survey.



EXPLANATION

- USGS study area boundary
- Patented bentonite claims
- Bentonite placer claims
- Bentonite layer depth (from surface, in feet)
  - -15–3
  - 3.1–15





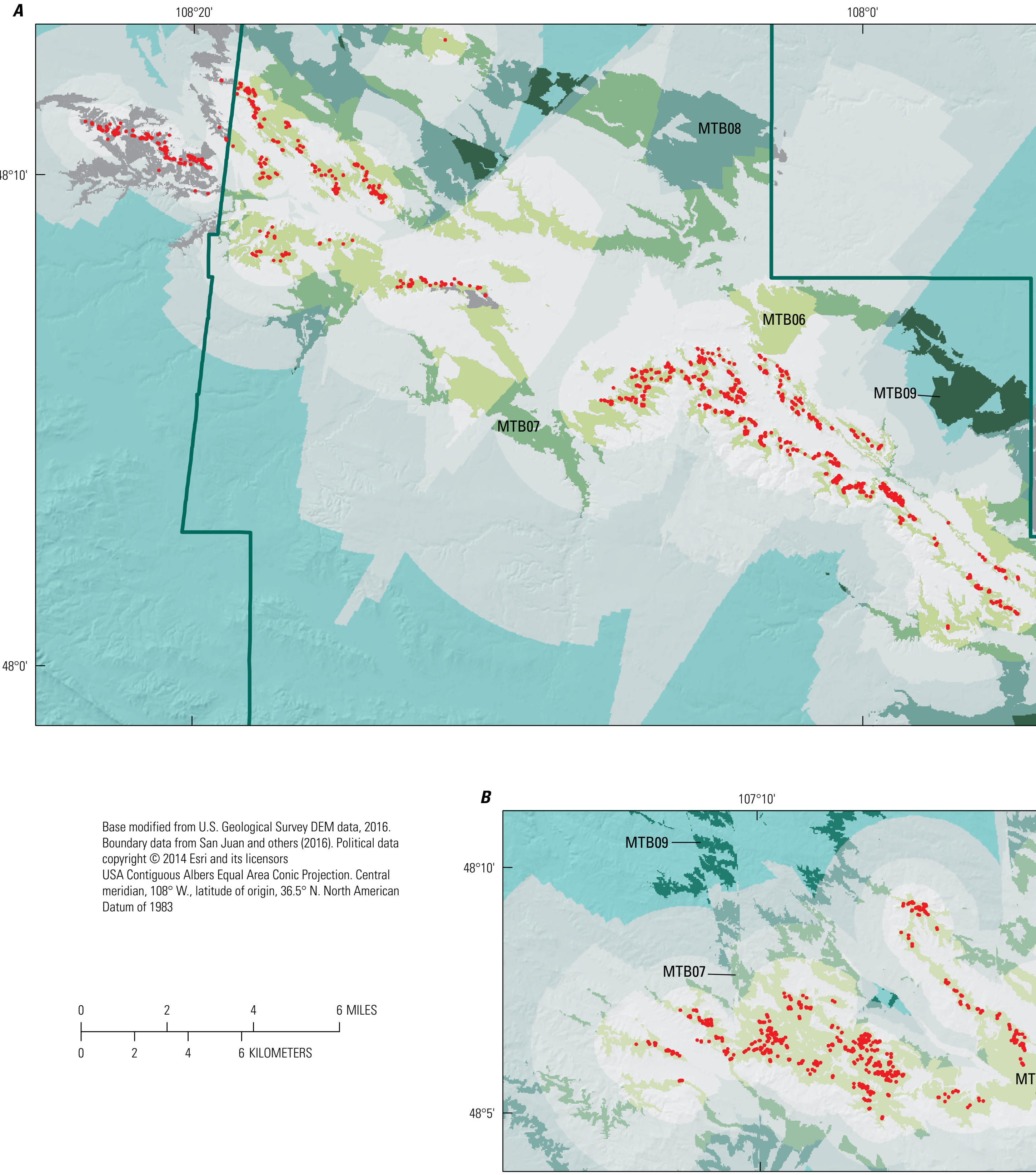
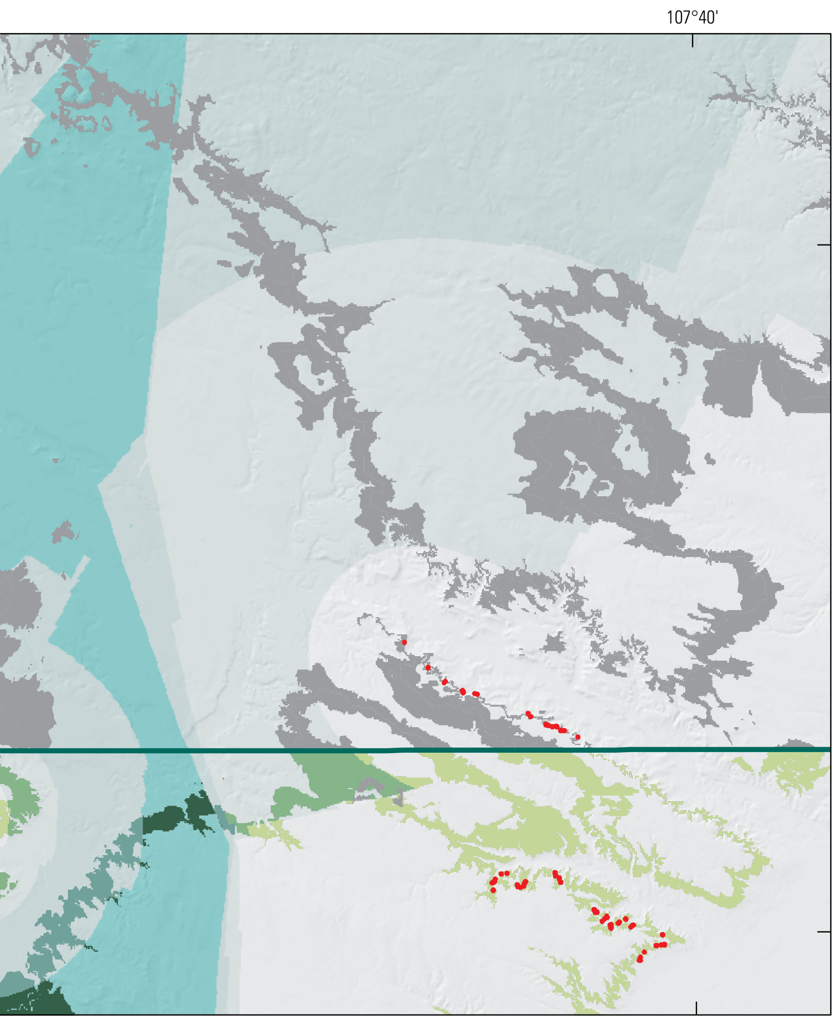


Figure 25. Maps showing prediction errors in the geostatistical surface used to generate the tracts shown in figure 27 for Malta, *A*, and Glasgow, *B*, areas, Montana. Tracts MTB06 through MTB09 are all high potential, but their certainties range from A to D. Errors increase away from control points. USGS, U.S. Geological Survey.



EXPLANATION

USGS study area boundary

Assessment tract type—Bentonite

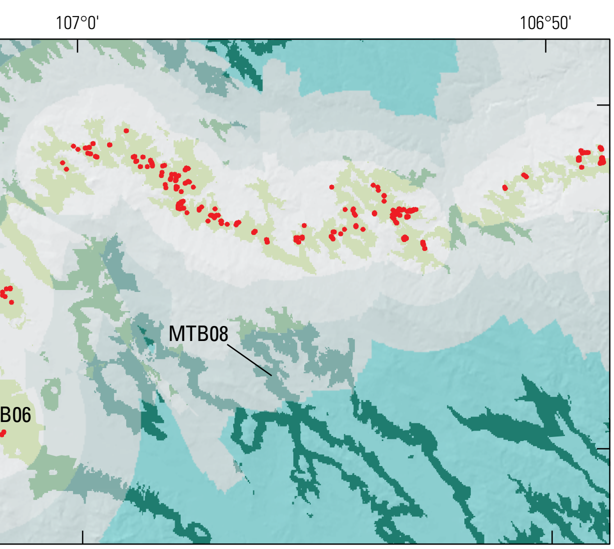
Bentonite layer 15 - 15 ft depth

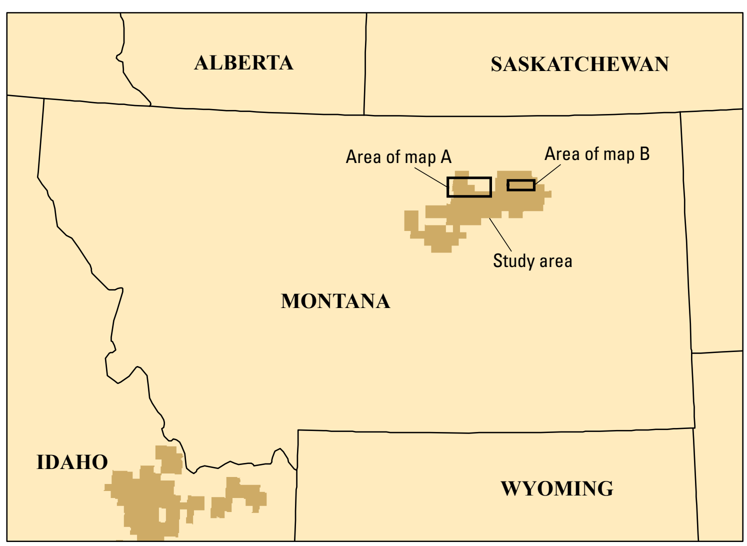
MTB06 - Certainty D
MTB07 - Certainty C
MTB08 - Certainty B
MTB09 - Certainty A
Outside study area

Prediction error

1.57–23.5
23.5–36.6
36.6–53.2
53.2–152

Control points for base of upper bentonite layer





Geostatistical methods (kriging) were used to generate surfaces for the top of the Judith River Formation using the entire dataset and just those drillholes in the study area. Using simple kriging, model errors were not acceptable; mean standardized was not equal to or close to zero, and root mean square standardized was not equal to or close to one. Given the limited data in the study area and the model errors for the geostatistical approach, we decided to use a deterministic method to create a continuous surface for the top of the Judith River Formation. The ArcGIS Topo to Raster tool was used to create the surface for the elevation of the upper contact of the Judith River Formation.

Using raster calculations in ArcGIS, the stratigraphic distances from the top of the Judith River Formation to the lower and upper contacts of the bentonitic interval in well SZ-1 were added to the Judith River elevation surface to create hypothetical elevation surfaces for the bottom and top of the bentonite-rich interval. Using raster calculations in ArcGIS, the bentonite surfaces were subtracted from a 90-m digital elevation model to estimate where the stratigraphic surfaces should intersect the ground surface. Where the stratigraphic and the ground surfaces intersect, the subtraction raster has a value of zero. The zero values were plotted on a map to show where the bentonitic surfaces should crop out.

The model results were then compared with the maps of mineral patents and active placer claims located for bentonite, as well as the maps we created showing the distribution of concretions associated with bentonite beds in the Malta and Glasgow areas. The model performed well for areas near dry hole SZ-1, but poorly to the east.

The model was not good because the assumption of constant thickness from the top of the Judith River Formation to the base of the bentonitic interval in the Bearpaw Shale was incorrect. The Bearpaw Shale is a transgressive marine unit that conformably overlies the Judith River Formation (Knechtel, 1959; Gill and Cobban, 1973). During the Cretaceous Period, sea level rose and oceans transgressed across the central part of North America, creating the Western Interior Seaway (fig. 17). Nearshore, coarser grained clastic material, such as sand, was deposited; offshore, fine-grained material, such as silt and clay, accumulated. During marine transgressions, the shoreline moves towards higher ground, and with it, the coarser grained sedimentary facies. The Bearpaw Shale was deposited during the last substantial marine transgression in the Cretaceous Period. This resulted in the movement of deepwater environments (shales of the Bearpaw) to areas formerly characterized by nearshore, shallow water conditions (sandstones of the Judith River Formation). As a result, the Bearpaw Shale forms a western-thinning wedge of shale (thinner towards the western shore of the Western Interior Seaway and thicker towards the deeper part of the basin) and the contact between the Judith River Formation and the Bearpaw Shale becomes younger to the west. Therefore, the distance between the top of the Judith River Formation and an overlying time-horizon, such as a bentonite layer, is not constant. The separation distance should increase towards the east, away from the western shore of the Western Interior Seaway.

We applied a simple linear correction to account for the increasing stratigraphic separation between the top of the Judith River Formation and the bentonitic interval in deeper parts of the Western Interior Seaway (fig. 20). A section of the Bearpaw Shale in the Kaycee District in Wyoming provided an initial estimate of values to use to estimate the distance between the top of the Judith River Formation and the Bearpaw Shale bentonite-rich interval. We assumed the shoreline was approximately north-south in Bearpaw-Shale time and used the separation distances in well SZ-1 and the Kaycee District to create a raster file of separation values to add elevation of the top of the Judith River Formation. After applying a facies correction, the predicted outcrop pattern for the bentonite-rich interval was consistent with mapped distribution of concretions and mining claims. In the areas where bedrock is exposed, interpretation of surficial mineralogy from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery confirmed the presence of smectite in those areas where the model indicated the bentonite-rich interval should crop out (Rockwell and others, 2015; Rockwell, 2016). The model also predicted that the bentonite-rich interval in the Bearpaw Shale to be exposed along the Missouri River over the area where the Siparyann bentonite bed is known to occur in the Charles M. Russell National Wildlife Refuge (fig. 21*B*; Miller and others, 1979).

Bentonite in the Fox Hills and Hell Creek Formations: Tracts MTB04 and MTB05

Bentonite is also present in the Fox Hills and Hell Creek Formations that crop out the southeastern part of the study area. For the potential map, the distribution of these map units was extracted from 1:100,000-scale geologic maps provided by the Montana Bureau of Mines and Geology (2016). No modeling was required because the existing maps were sufficient to show the distribution of rocks with bentonite potential; steps to determine potential and certainty of these tracts are described in the following section.

Mineral Potential of Bentonitic Units Outside the Malta and Glasgow Areas

In order to determine mineral potential and certainty, these models and maps were combined with a surficial geologic map that distinguishes areas underlain by weathered bedrock from areas overlain by overburden of glacial till or alluvial deposits. The amount of overburden determines if a bentonite bed is a potential resource. As noted previously, bentonite is mined from open pits that rarely extend to depths of 15 m with maximum strip ratios of about 10:1. Only those beds close to the surface have any potential to be exploited. The models and approaches described in the previous section predict where bentonite-bearing units should crop out. If they are covered by younger surficial sediments or are in an area of steep terrain, there could be too much overburden for the beds to be a potential resource.

In order to integrate cover and overburden into the potential map, a surficial map was derived from soil maps prepared by the Natural Resources Conservation Service (Montana State Library, 2016b). Soil map databases for the five counties that intersect the study area were queried to extract the parent material of the soil map units. The soil-map-unit descriptions were used to code parent material if the information was missing from the database. The data for the counties was merged, dissolved, and clipped to create the map used in the analysis. The Natural Resources Conservation Service provides detailed descriptive names for parent material based on the grain size of the parent material and (or) the lithology of the bedrock source. These specific, descriptive names were grouped into fewer units based upon common characteristics. For example, parent material called clayey alluvium, coarse-loamy alluvium, gravelly alluvium, loamy alluvium, sandy alluvium, and silty alluvium were grouped into a category we called alluvium. Complex parent material descriptions were recoded to create a spatial database with fewer than a dozen categories of parent material.

The distribution of surficial units was merged with the modeled outcrop distribution of the bentonite-rich interval in the Bearpaw Shale and the known extent of the Fox Hills and Hell Creek Formations to create the potential map for the study area outside the Malta and Glasgow areas (fig. 26; tracts MTB01 to MTB05, appendix 2; San Juan and others, 2016). The assumption behind combining these two themes is that areas covered by glacial till and alluvium could have lower potential because the till and alluvium may be too thick, or alluvial or glacial processes could have removed the bentonite beds by erosion (fig. 22*D*).

Terrain also affects the amount of overburden and the resource potential of bentonite beds. Throughout the study area, the bentonite beds are relatively flat-lying, with dips of 1–2º. In the Malta and Glasgow areas, bentonite beds are exposed and the slope is sufficiently low such that the amount of overlying rock does not increase substantially over considerable lateral distances. In parts of the study area near the Missouri River, the bentonite beds are exposed in steeper valleys and are 60–90 m below the upland surface (Miller and others, 1979). If the bed is followed into the hillside, the amount of overlying rock will increase substantially over short distances. Because of the geometry of the layers relative to the upland surface and the valley walls, the stripping ratio could range from 0:1 to 50:1 in little more than a kilometer. Therefore, areas where the bentonite-rich interval is predicted to occur, and which are underlain by weathered bedrock with shallow slope, were ranked high potential (tract MTB01, appendix 2, fig. 26; San Juan and others, 2016). Areas where the bentonite-rich interval is predicted to be present and exposed, but with steep slopes and poor accessibility, were ranked “moderate potential” (tracts MTB02 and MTB04, appendix 2, fig. 26; San Juan and others, 2016). Areas where the bentonite-rich interval is predicted to be present, but is covered by extensive surficial deposits, are ranked “low potential” (tracts MTB03 and MTB05, appendix 2, fig. 26; San Juan and others, 2016).

Ideally, this assessment should consider the grade of the bentonite beds (the amount of montmorillonite present), the physicochemical properties of the clay minerals, and the presence of any deleterious material, such as gypsum, that would affect end use. General statements about the quality of a particular bentonite deposit are difficult to make because of the amenability of bentonite to blending or treatment with additives to enhance its properties. New uses continue to be identified (for example, Carrado and Komadel, 2009; Gates and others, 2009; Güven, 2009) and standards for testing continue to be updated (American Petroleum Institute, 2011). Previous standards used to evaluate the use of bentonite as a taconite binder have been eliminated and not replaced (ASTM International, 1997). The old and limited publically available data on the grade and quality of the bentonite in the study area (Berg, 1969; Bigsby and Sollid, 1975; Miller and others, 1979; Durst, 1981) really cannot be used to make conclusions about its potential value now and in the future.

Economic Analysis of the Deposit Type

The most important bentonite resource in the study area is associated with the X and Y bentonite beds in the Malta and Glasgow areas, and their extensions. The bentonite beds are more than a meter thick, are continuous, and occur in areas with relatively low relief that would have relatively low stripping ratios if the beds were covered by overburden. These beds are also close to a major rail line that could transport material to markets.

The Siparyann bed in the Bearpaw Shale is relatively thick and continuous (fig. 21*B*), but it occurs in an area where the amount of overburden exceeds the economic strip ratio. The steep terrain where the bed is exposed limits areas with low overburden to long narrow strips along the sides of steep valleys (Miller and others, 1979).

The bentonites in the Fox Hills and Hell Creek Formations are laterally discontinuous and are in areas with limited accessibility (Miller and others, 1979). The Hell Creek bentonites have been used as sealants for stock ponds and irrigation ditches by local ranchers, but many other deposits of material with comparable quality exist nearby.

The domestic and global commodity summary for bentonite (appendix 5 in Day and others, 2016; Bleiwas, 2016) indicates that bentonite is an important commodity now and will continue to be in the future. As an example, from 1990 to 2014 the compound annual growth rate in domestic production was approximately 1.4 percent. Given the broad range of uses for bentonite and the growth of demand and production, one could ask why there has been little bentonite produced from the Malta and Glasgow areas in the 60 years since the beds were discovered.

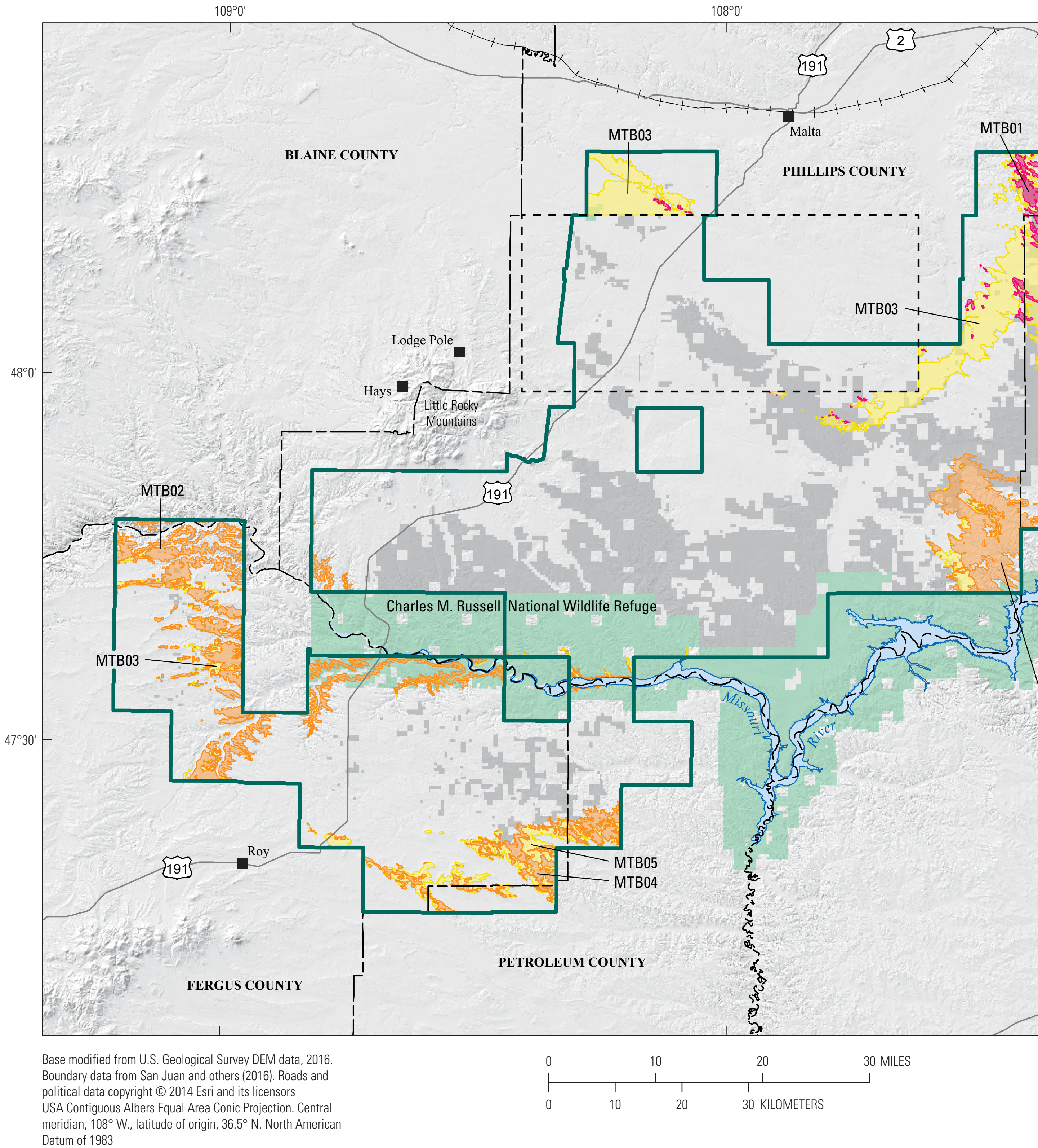
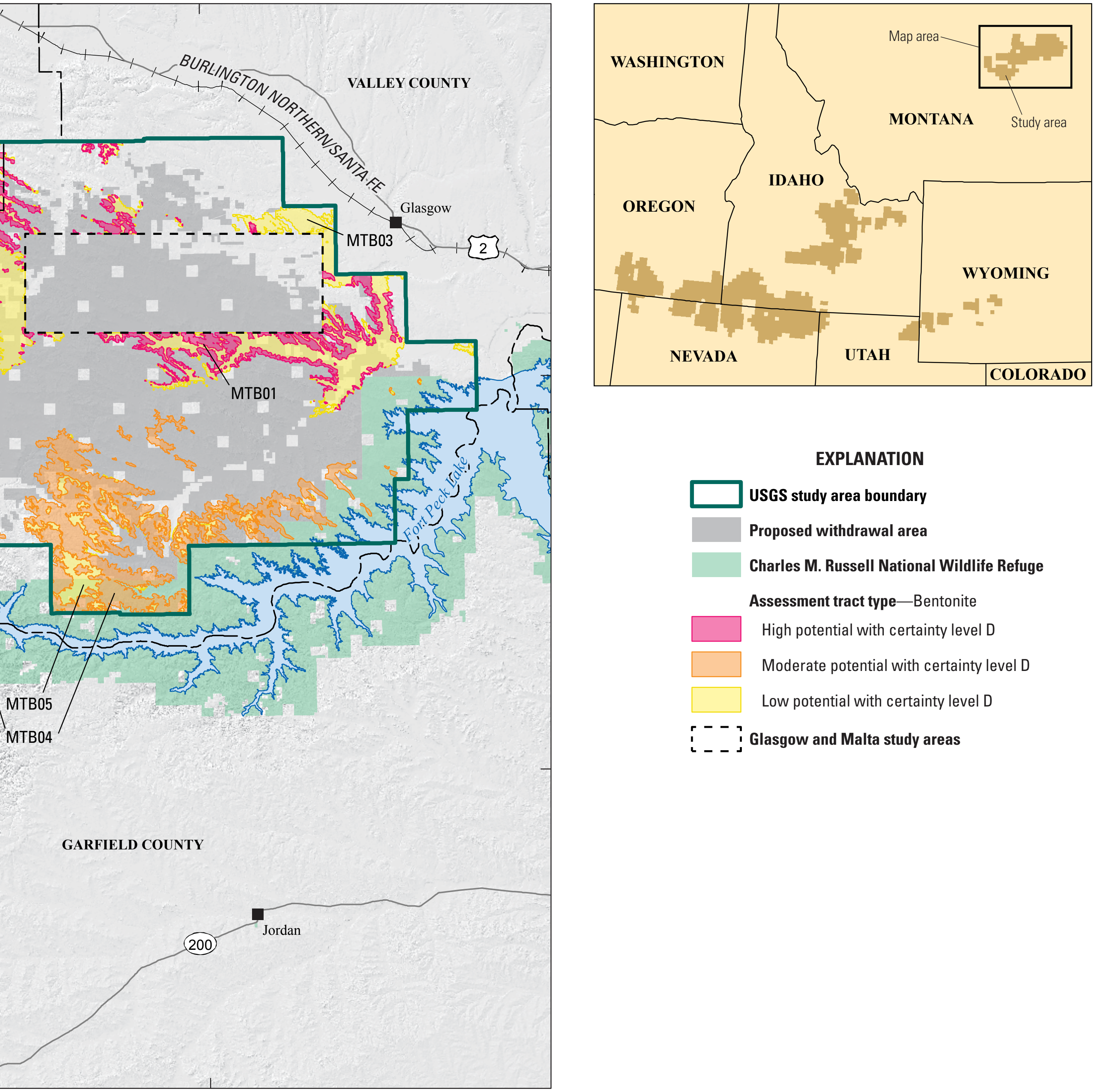
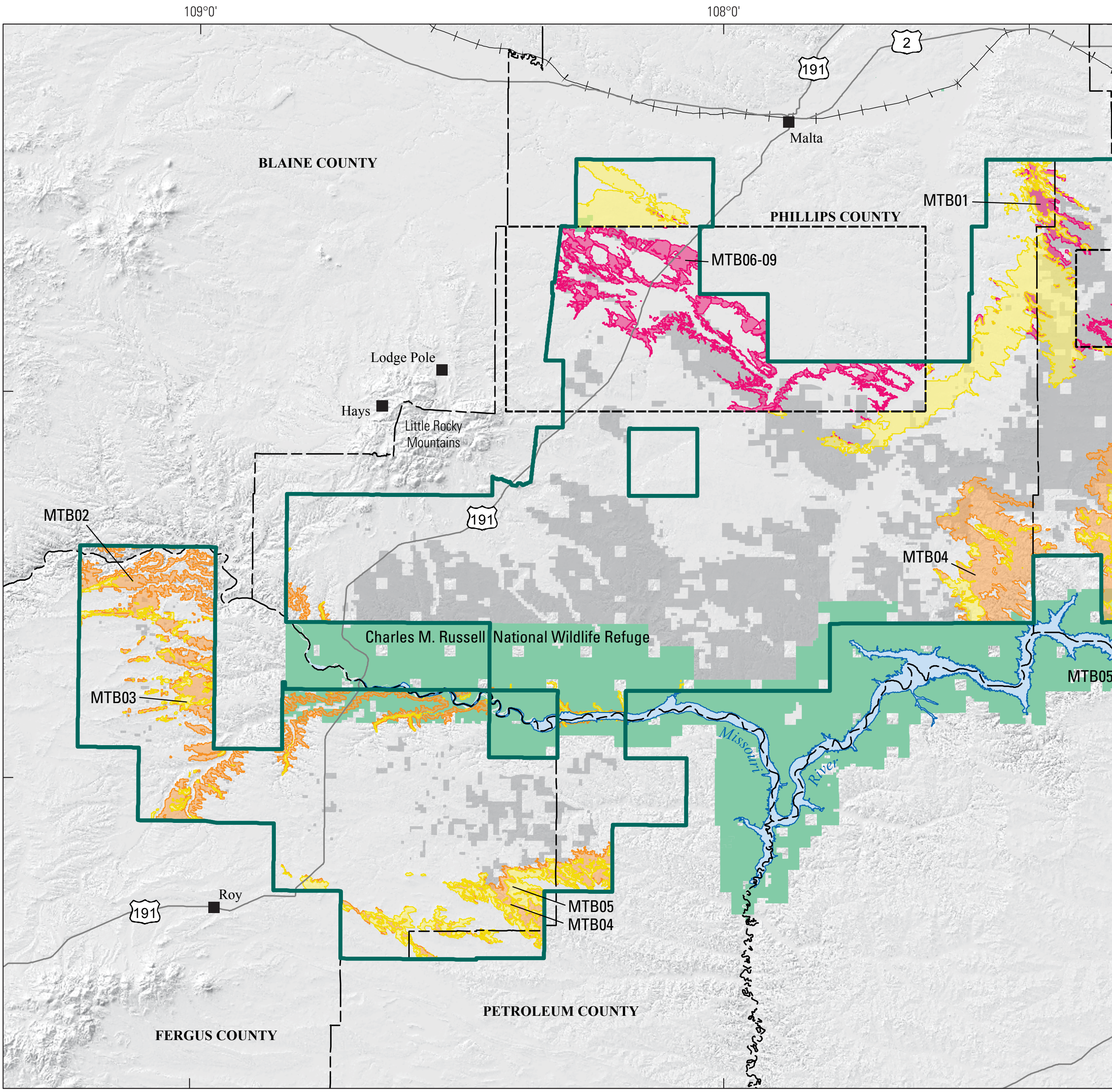


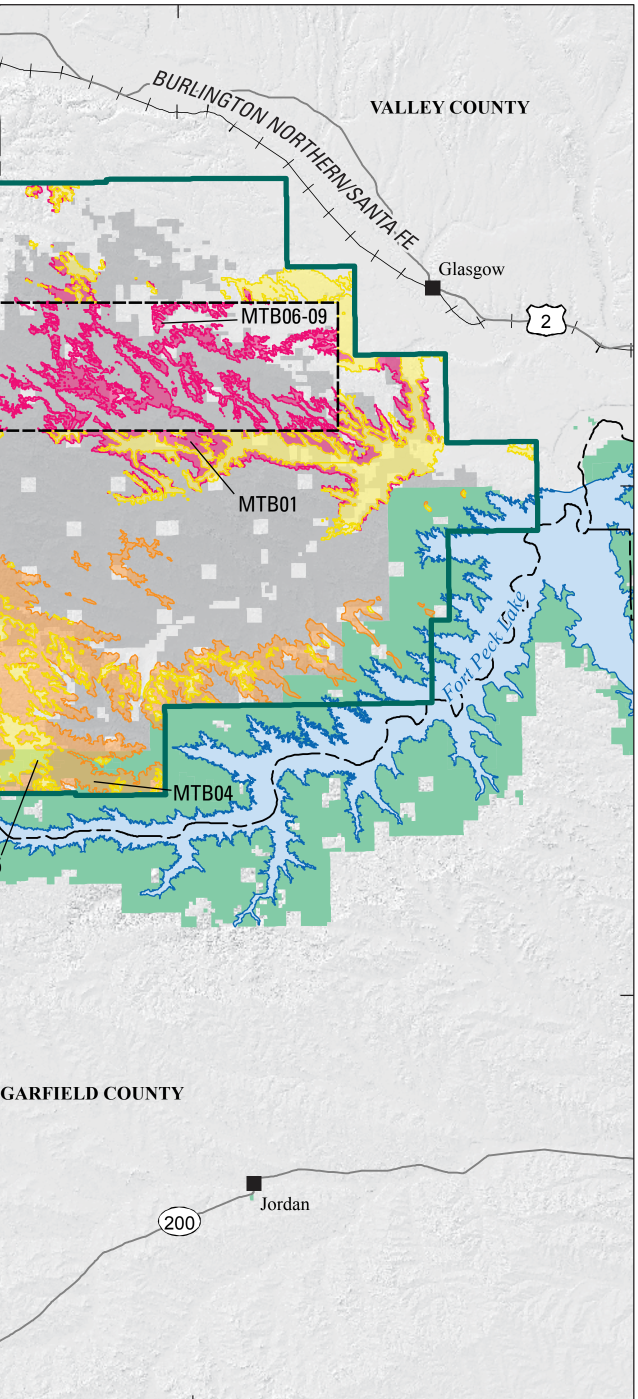
Figure 26. Mineral potential map for sedimentary bentonite deposits in the bentonitic interval in the Bearpaw Shale and in the Fox Hills and Hell Creek Formations, in the North-Central Montana Sagebrush Focal Area. The potential map is based on combining data themes that map the possible distribution of the bentonitic interval based on stratigraphic, facies, and terrain analysis with a surficial map of the study area. USGS, U.S. Geological Survey.

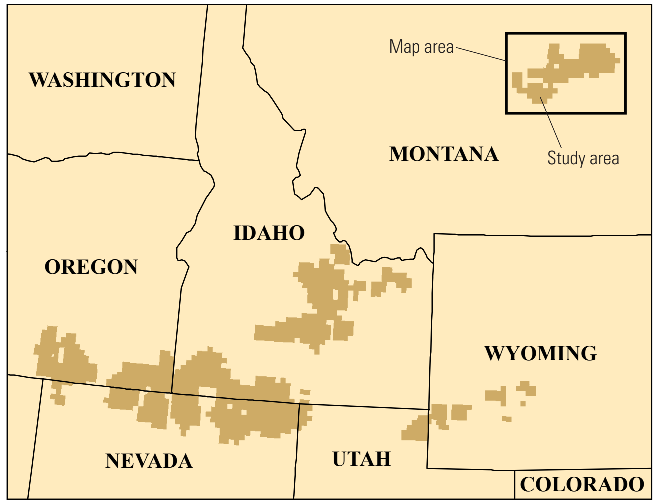

107°0'
BURLINGTON NORTHERN/SANTA FE
VALLEY COUNTY
Glasgow
2
MTB03
MTB01
Fort Peck Lake
MTB05
MTB04
GARFIELD COUNTY
Jordan
200
WASHINGTON
Map area
MONTANA
Study area
OREGON
IDAHO
WYOMING
NEVADA
UTAH
COLORADO
EXPLANATION
USGS study area boundary
Proposed withdrawal area
Charles M. Russell National Wildlife Refuge
Assessment tract type—Bentonite
High potential with certainty level D
Moderate potential with certainty level D
Low potential with certainty level D
Glasgow and Malta study areas



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 27. Mineral potential map for sedimentary bentonite deposits in the North-Central Montana Sagebrush Focal Area. This map shows how the two approaches used to assess bentonite in the study area were integrated for the geographic information system database that accompanies the assessment reports (San Juan and others, 2016). USGS, U.S. Geological Survey.





EXPLANATION

USGS study area boundary

Proposed withdrawal area

Charles M. Russell National Wildlife Refuge

Assessment tract type—Bentonite

High potential with certainty levels A, B, C, and D

Moderate potential with certainty level D

Low potential with certainty level D

Glasgow and Malta study areas

One reason could be related to broader trends in the energy and steel industries. The price of bentonite in the last 60 years is broadly correlated to the price of oil, rig counts, and the price of steel (fig. 28). As the industry values of oil and steel wax and wane, so does the demand for bentonite. The only time bentonite was produced in the study area was during the early 1980s when crude oil and steel prices were both relatively high. Other reasons for low production include changes to the legislative and regulatory environment as summarized in table 7. For example, imposition of maintenance fees for mining claims, and a moratorium on mineral patents more than likely suppressed exploration and mining activity in the study area, particularly when combined with a downturn in the oil and steel industries. A new State law enacted in 2005, which reduced the tax burden on bentonite production, made it more likely that bentonite could be mined in the area (Montana Tax Foundation Inc., 2007; Montana Department of Revenue, 2014; Montana Legislative Services, 2015).

Future development will likely be affected by the energy and steel markets, the tax burden imposed by government, and the overall regulatory environment.

Magmatic System: Diatreme-Hosted Diamond Deposit Type

Diamond is a crystalline form of elemental carbon that forms at extremely high temperature and pressure conditions that are possible only very deep in the Earth's upper mantle. Large diamonds, particularly large diamonds without flaws, and colored diamonds are extremely rare and are very valuable as gemstones. The majority of diamonds, however, are small,

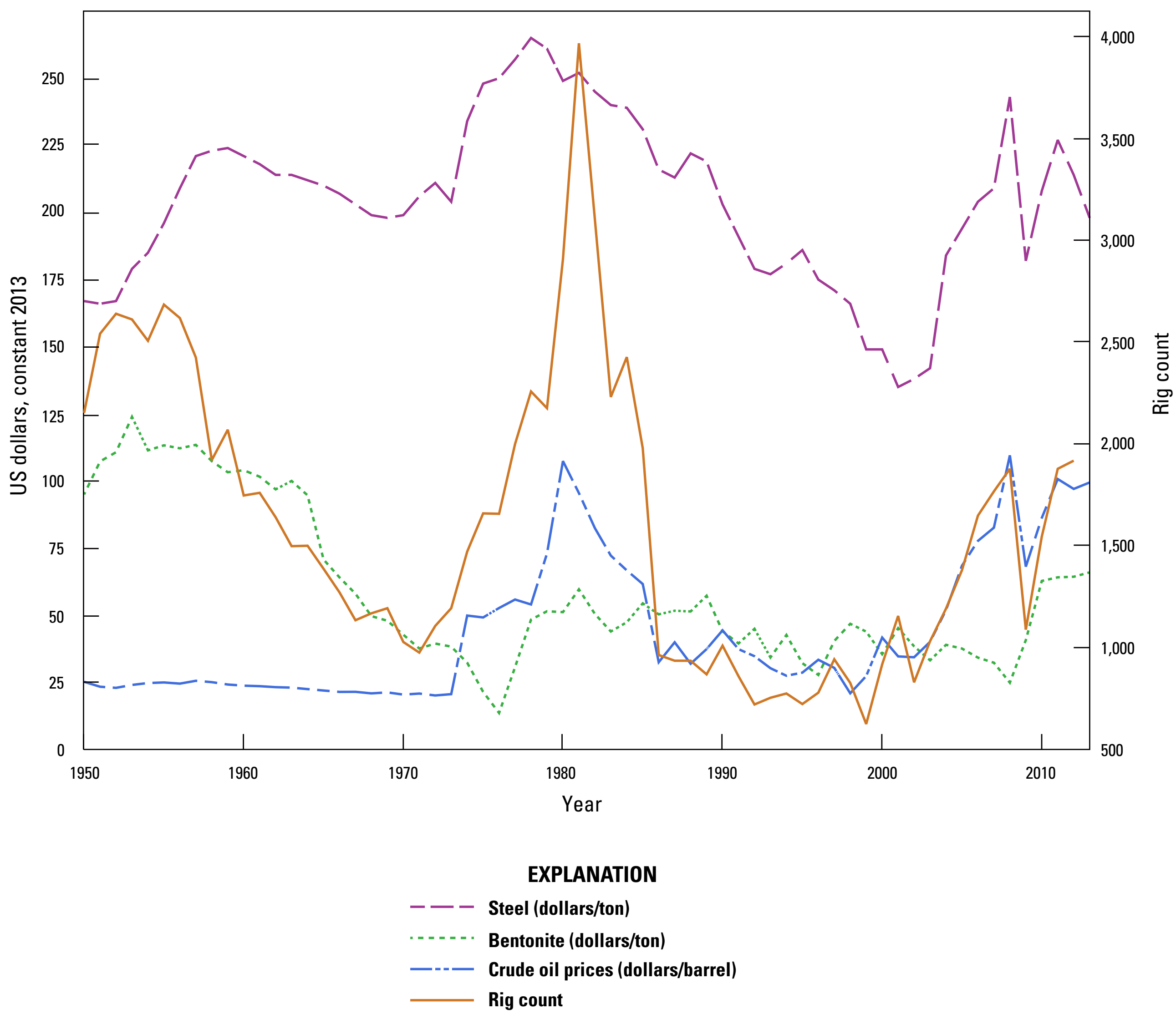


Figure 28. Graph showing steel, bentonite, and crude oil prices and the number of drilling rigs in the United States from 1950 to 2013. Prices are recalculated to constant dollars as of 2013. Modified from U.S. Geological Survey (2014), Macrotrends LLC (2016), and U.S. Energy Information Administration (2015).

flawed, and contain dark impurities. These small non-gem diamonds have a variety of industrial uses as abrasives, in drill bits, and to coat saw blades for stone and concrete cutting.

Mineral Description

Kimberlite and lamproite diatremes and hypabyssal intrusions are the only two primary sources of diamonds in the world (for example, Groat and others, 2014; appendix 3 in Day and others, 2016, and references therein). The age of diamond formation is much older than the age of magmatism that transports diamond to the surface (Gurney and others, 2010). Occurrence of diamond in kimberlite or lamproite depends on two important factors: (1) formation and preservation of diamond in upper mantle rocks and (2) rapid transport of diamond to avoid conversion to graphite or oxidation to CO or CO_2 during the upward movement of kimberlitic and lamproitic magmas through diamond-bearing mantle rocks to the surface (Mitchell, 1993; Gurney and others, 2010; Stachel and Luth, 2015).

Diamonds occur in mantle keels, the thickened parts of the lithospheric mantle that underlie continental crust of Archean cratons, at depths below the graphite-diamond transition zone. Kimberlitic and lamproitic magmas are derived by small amounts of melting deep within the mantle or in the asthenosphere, have relatively high volatile content, are MgO-rich, and are less oxidized than basaltic magma. These low-viscosity, volatile-rich melts erupt rapidly by hydraulically fracturing the overlying rocks; the ascent of these melts is thought to be one of Earth's most dynamic volcanic processes (Shirey and Shigley, 2013). The rapid upward transport of diamond crystals prevents them from being completely dissolved and resorbed into the melt. Even so, most diamond crystals show external patterns of resorption.

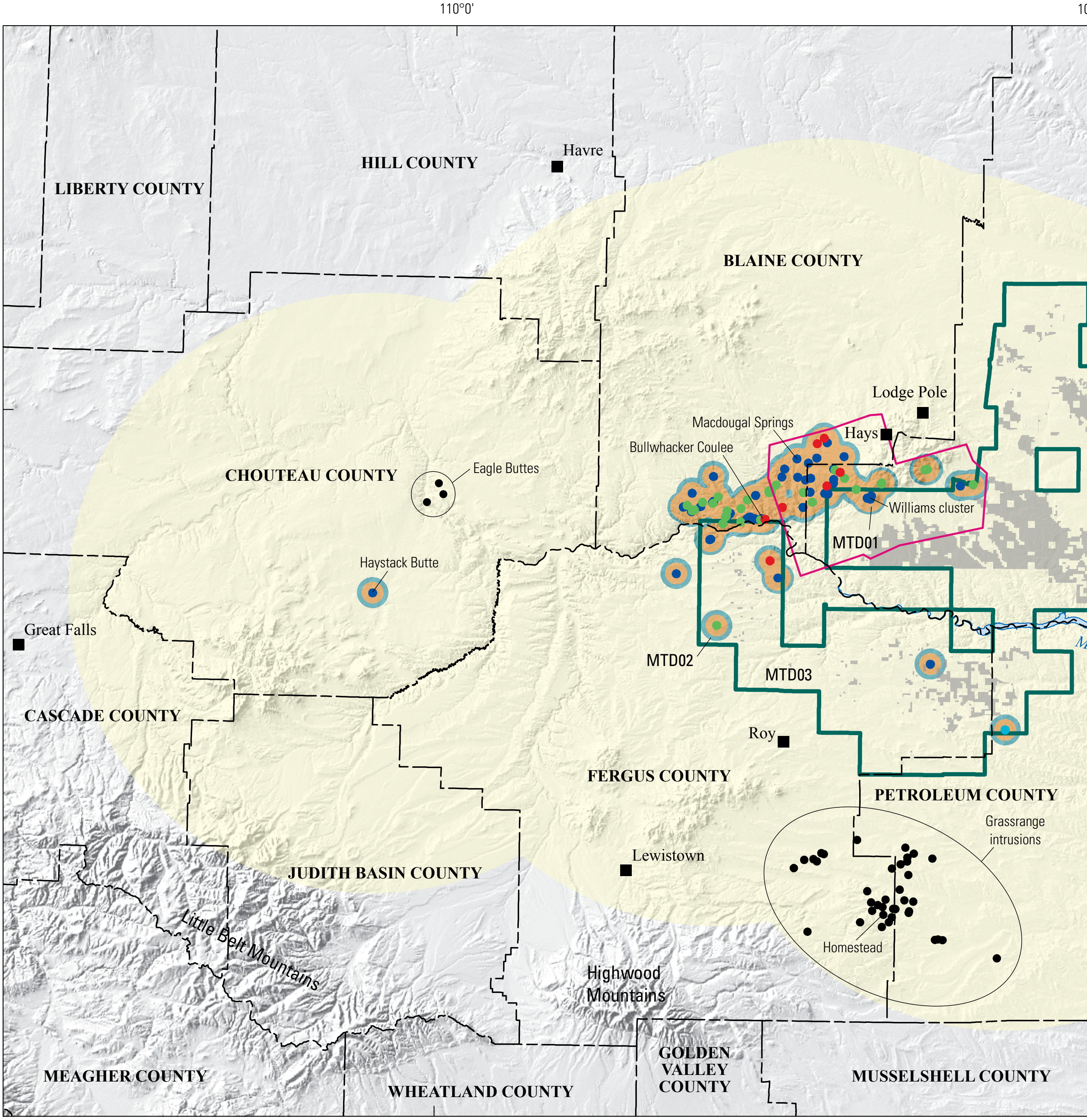
Within Archean cratons, kimberlites and lamproites occur in clusters, fields, and provinces (Mitchell, 1986). Kimberlites and related rocks are commonly associated with major lineaments and fault zones that correspond to major zones of weakness in the lithosphere; these zones appear to control the ascent from the upper mantle. The tectonic forces responsible for triggering mantle melting to produce kimberlite are still debated (Helmstaedt and Gurney, 1994; Heaman and others, 2003). The presence of mantle keels under the continents appears to affect where kimberlitic volcanism takes place by slowing the rise of upwelling mantle, at about the depth where carbonate-bearing peridotite could begin to melt (Shirey and Shigley, 2013). Under these conditions, volatile-rich melts separate to form volatile-enriched kimberlite magma that migrates rapidly upwards through the crust. The location of intrusions at or near the surface is determined by local and regional geologic and structural features, such as proximity to faults and mafic dike intersections (Mitchell, 1986).

Worldwide, only 1 in 10 kimberlites is diamond-bearing, and only 1 in 10 diamond-bearing kimberlites is economically mineable (Janse and Sheahan, 1995). In their global compilation, Janse and Sheahan (1995) recognized 5,000 kimberlite intrusions—500 are diamondiferous, 50 have been or are being mined, and 15 are large active mines. Now, more than 10,000 kimberlites are known worldwide (Gurney and others, 2010), but only about 1 percent are commercially viable diamond mines.

Kimberlites and lamproites are mixtures of xenoliths of crustal rocks and mantle, minerals separated from disaggregated xenoliths, phenocryst minerals, alteration minerals, and pieces of preexisting kimberlitic or lamproitic rock (Shirey and Shigley, 2013). Even if all conditions are met, diamonds are always trace minerals in the host kimberlite and can be difficult to find. Instead, indicator minerals that are geologically associated with diamonds, but are much more abundant, are used to explore for diamond deposits. Indicator minerals are derived from upper mantle peridotites and other upper mantle inclusions. For example, mantle-derived garnets show compositional variations that allow them to be put into groups. The term G10 is used for, calcium-undersaturated (subcalcic), or harzburgitic peridotitic garnets, whereas G9 represents calcium-saturated or lherzolitic peridotitic garnets (Grütter and others, 2004). Indicators for diamonds derived from peridotite are G10 pyrope garnets with enriched Cr and depleted Ca, chromite with enriched Cr and Mg and depleted Al and Ti, diopside with enriched Cr and Al, and orthopyroxene with enriched Mg/(Mg+Fe) ratios. For diamonds derived from eclogite, Cr-poor garnets with enriched Na and Ti and diopside with enriched Na are common indicator minerals (Shirey and Shigley, 2013).

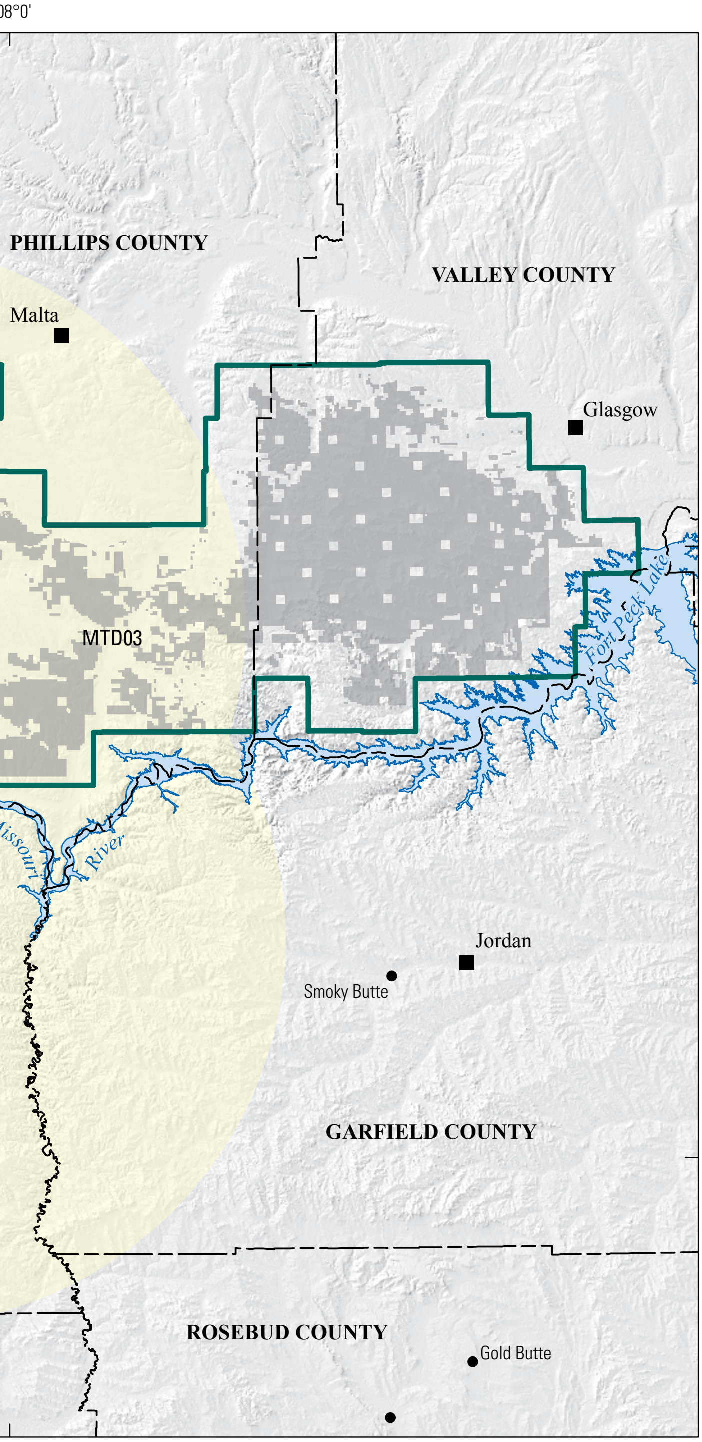
Geology and Occurrence in the Study Area

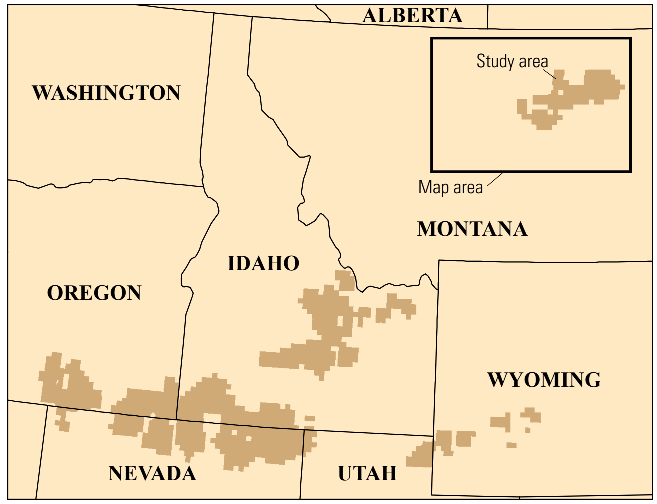
The Central Montana alkaline province contains Late Cretaceous to Eocene alkalic rocks that include clusters of diatremes, dikes, and plugs that range in composition from alkaline ultramafic to carbonatites (fig. 29). A few of the occurrences are kimberlitic in affinity. The study area includes part of the Missouri River Breaks diatreme field, and the cluster of Grassrange intrusions is immediately south of the study area. Because of the presence of kimberlitic rocks, both areas have been explored for diamond.



Boundary data from San Juan and others (2016).
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 29. Map showing the location of diatremes and related igneous rocks in the study area and the surrounding region (modified from Hearn, 1979, 2004; McGee and Hearn, 1989; Irving and Hearn, 2003; Faure, 2010; Anderson and others, 2016). Map also shows mineral potential for diamond deposits in the North-Central Montana Sagebrush Focal Area. USGS, U.S. Geological Survey.





EXPLANATION

USGS study area boundary

Proposed withdrawal area

Assessment tract type—Diatreme-hosted diamond

Low potential for diamonds

Certainty level B

Certainty level C

Certainty level D

Extent of Anaconda aeromagnetic survey

Missouri River Breaks intrusions

Diatreme

Diatreme inferred from geophysics

Major or unusual dikes and plugs

Connoly Coulee baked sandstone

Other intrusive centers, diatremes, and dikes

Missouri Breaks Diatremes

The Missouri River Breaks diatremes form an east-northeast-trending band of ~50 ultramafic alkalic diatremes (including satellitic pipes) and additional dikes and plugs, which range from 52 to 47 Ma, in the Missouri River Breaks area of north-central Montana (Hearn, 1968, 1979; Marvin and others, 1980). The diatremes and intrusions were produced by alkalic ultramafic magmas that mainly crystallized to melnoites and lesser amounts of other rocks such as kimberlites, aillikites, and carbonatites. Their fine-grained fresh equivalents, which would correspond to potassic olivine nephelinite or olivine melilitite, are typically altered to secondary minerals in bedded pyroclastic deposits within the diatremes. In other parts of the world, similar alkalic ultramafic magmas occur in the same broad geographic areas as kimberlites, and may have been parental to kimberlites (Dawson, 1980). Although the alkalic ultramafic character of the Missouri River Breaks diatremes indicates kimberlitic affinity, only the Williams diatremes, which are one cluster of four closely spaced occurrences, can be termed true kimberlite on the basis of the presence of the typical kimberlite indicator minerals chromian pyrope garnet, chromian diopside, enstatite, and magnesian ilmenite (Dawson, 1980).

The Williams cluster of kimberlite occurrences is located on the west side of Thornhill Butte (also known as Cyprian Butte, Sippary Ann Butte, and Sipparyann Butte), a syenite-cored, faulted domal uplift on the southwest side of the Little Rocky Mountains (fig. 30). The largest occurrence, Williams 1, is 350 by 200 m, has an irregularly rounded shape, and shows a flat-topped positive magnetic anomaly (Hearn and McGee, 1984; Irving and Hearn, 2003). Williams 2 is a breccia body about 100 by 50 m with two short dike offshoots in uplifted Paleozoic limestone. Williams 3 is a nearly circular, 25-m pipe, with 10 percent kimberlite breccia and a large descended block of Telegraph Creek Formation that fills the rest of the pipe area. Williams 4 is a N. 32° E.-trending dike that is 380 m long and 10–30 m wide, which contains massive kimberlite and kimberlite breccia. Williams 1 and 4 contain xenoliths of garnet peridotite, garnet-spinel peridotite, spinel peridotite, and megacrysts (>1 cm) of garnet, chromian diopside, and magnesian ilmenite from the upper mantle (Hearn and McGee, 1984).

The only other Missouri River Breaks diatreme containing upper mantle garnet peridotites is the Macdougal Springs diatreme, which is 10 km northwest of the study area (McGee and Hearn, 1989). Partially altered xenoliths of garnet peridotite, garnet-spinel peridotite, and spinel peridotite contain fresh garnet, spinel, chromian diopside, and phlogopite, but all olivine and enstatite have been replaced by quartz and calcite. All garnets are purple to red G9 chromian pyrope garnets, and no G10 garnets are present.

Grassrange Intrusions

The Grassrange intrusions include aillikite, alnoite, carbonatite, kimberlite, and monchiquite, and occur as dikes, plugs, diatremes, and rare sills (Hearn, 2004). All of the Grassrange intrusions are south of the study area (fig. 29), but are discussed here because one of the occurrences is kimberlite that has been commercially tested, and many of the other rock types are similar to those of the Missouri River Breaks occurrences. Only the Homestead occurrence is kimberlite; the other intrusions are not.

The Homestead kimberlite has an irregular rounded shape (430 by 130 m) forms low hills in lower Colorado Group beds, and contains massive kimberlite and kimberlite breccia. The Homestead kimberlite has a marked positive magnetic anomaly. The kimberlite locally contains abundant xenoliths of garnet peridotite, garnet-spinel peridotite, spinel peridotite, and fewer websterites; megacrysts are absent (Hearn, 2004).

Exploration and Mining Activity

On a continental scale, geological and geophysical modeling can help identify Archean terranes with a history conducive to preserving diamonds at depth (Griffin and others, 2013). Geologic mapping, geophysical surveys, geochemical prospecting, and mineral studies aimed at identifying the presence of diamond-bearing mantle at depth are commonly used to evaluate specific targets.

Geophysical methods can accurately detect and map kimberlite and lamproite pipes (Macnae, 1995). Airborne magnetic surveys are the most cost effective; local anomalies may be of normal or reversed polarity compared to a non-magnetic background, depending on the remanent magnetization of the body. Airborne electromagnetic surveys are effective in detecting weathered or crater-facies pipes, and they can be used to discriminate targets where other nearby features may cause magnetic anomalies (Anderson and Ponce, 2016). In 1981, Anaconda Minerals Company contracted an aeromagnetic survey over part of the Missouri River Breaks field; the survey was roughly centered on the location of the Williams cluster of kimberlite diatremes (fig. 29). The analytic signal computed from the survey shows many of the known diatremes are characterized by short-wavelength, high-amplitude anomalies (fig. 31; Anderson and others, 2016).

Exploration for kimberlites in the field commonly is based on the occurrence of indicator minerals in soils, stream sediments, and glacial deposits in order to locate in-place, upstream, or up-ice kimberlite occurrences. Indicator minerals are recovered in heavy-mineral concentrates derived by panning samples in the field, separating material in a laboratory using heavy liquids, or using a hydraulic gravity-separation technique such as the Wilfley table. Chromian pyrope garnet and chromian diopside can be recognized in the field by their distinctive colors—purple to lavender for chromian pyrope garnet and bright (“traffic-light”) green for chromian diopside. Magnesian ilmenite, although not as distinctive, commonly has a shiny metallic gray appearance, and is non-magnetic or less magnetic than the usually abundant magnetite grains in heavy-mineral concentrates. The presence of high-chromium, low-calcium pyrope garnets (referred to as G10) in

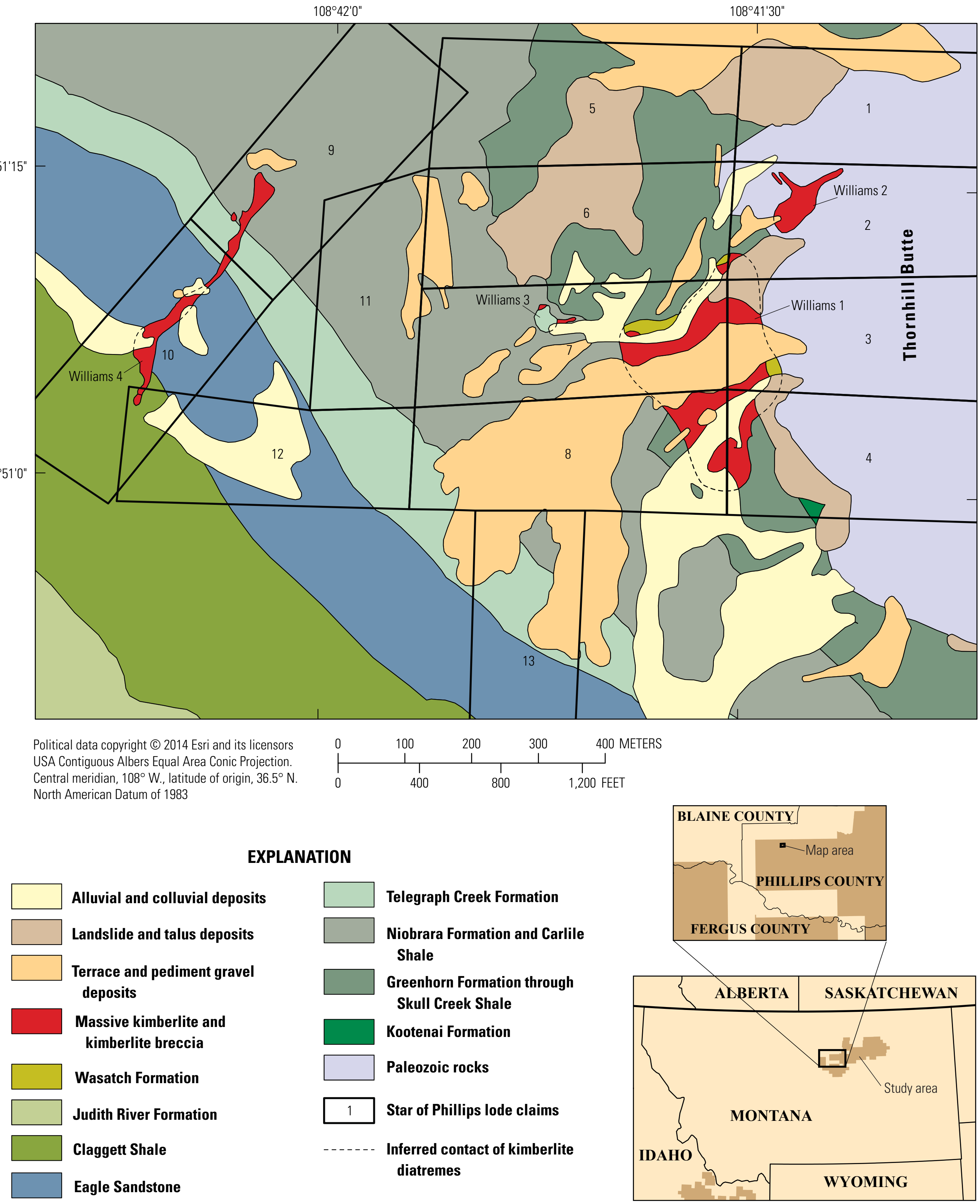


Figure 30. Detailed map showing the Williams cluster of kimberlite occurrences, geology, and location of claims (modified from Hearn and McGee, 1983; Nathaniel Arave, Bureau of Land Management, Billings, Montana, written commun., 2016).

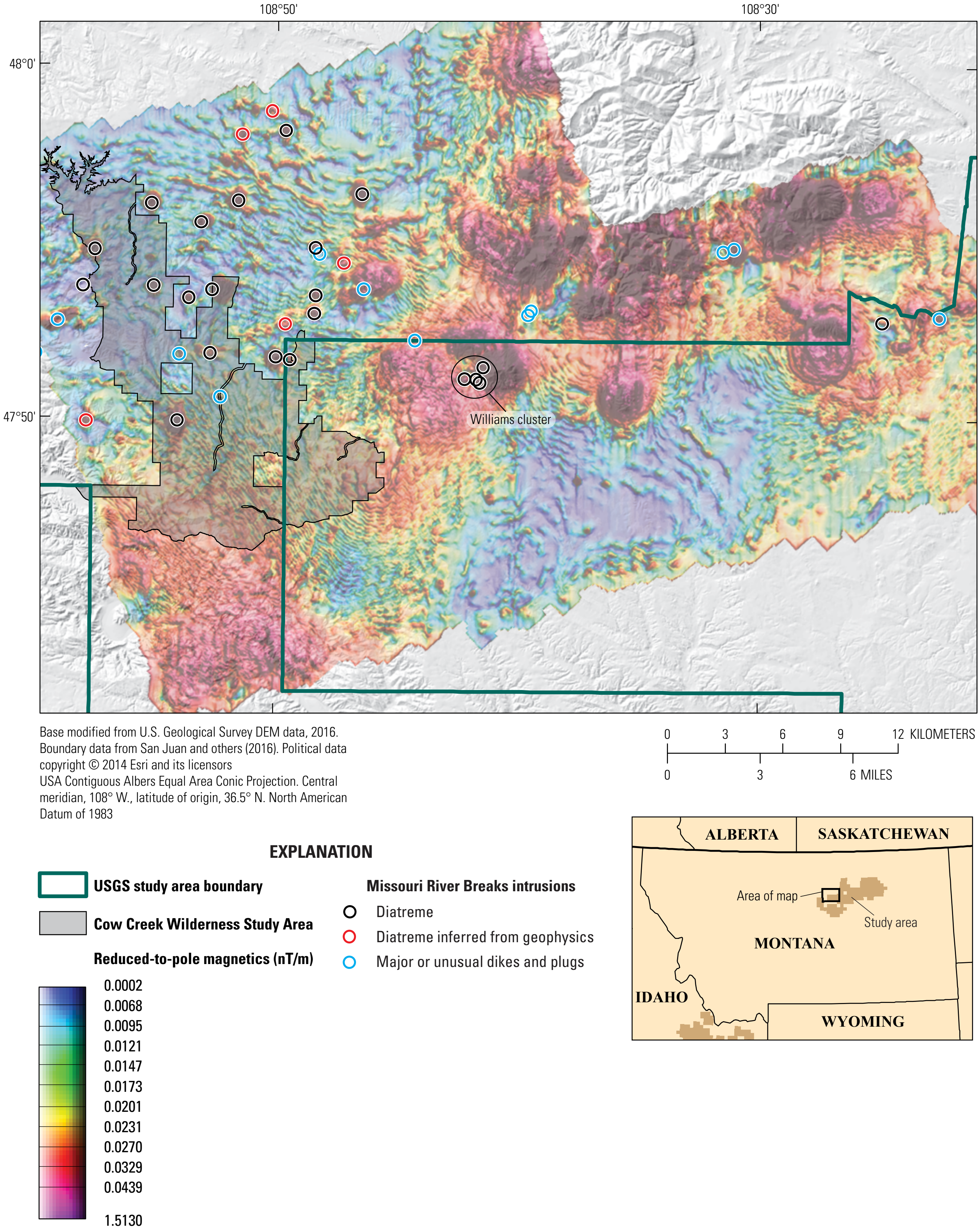


Figure 31. Map showing analytic signal results from a high-resolution aeromagnetic survey by Anaconda Minerals Company (Anderson and others, 2016) and the location of known and inferred diatremes. Known and inferred diatremes are small features, typically less than 0.5 km across, which are characterized by short-wavelength, high-amplitude anomalies. USGS, U.S. Geological Survey. nT/m, nanotesla per meter.

heavy-mineral concentrates from kimberlite is favorable for occurrence of diamond (for example, Grütter and others, 2004; Groat and others, 2014, and references therein).

In addition, pressure and temperature relations in the mantle can be deduced from the composition of minerals. Equilibrium temperature and pressure conditions for the upper mantle sources of garnet peridotite xenoliths can be calculated from a variety of mineral compositions, using several formulas based on mineral syntheses and thermodynamic calculations. Temperatures and pressures estimated from mineral compositions in xenoliths can be plotted relative to the graphite-diamond stability boundary to evaluate whether diamond-bearing mantle rocks underlie the region (fig. 32).

Exploration activity on the Missouri River Breaks diatremes between 1976 and 2010 can be inferred from the compilation of mining claim information (Causey, 2011). The number of lode claims on diatremes increased considerably between 1976 and 1977. The number of claims continued to gradually increase, peaking in 2003. The number of claims decreased beginning in 2004, and continued to decrease through 2010. By 2016, the only active claims in the study area were on the Williams cluster of kimberlites (Star of Phillips lode claims 1–13), and on the Saskatchewan Butte 2 diatreme (HAL 40 lode).

Williams Kimberlites

The Williams 1 and 4 kimberlites were thoroughly explored in 1979–1980 by Anaconda Minerals Company (Ledford, 1981). An on-site separation plant to recover heavy-mineral concentrates processed 312 metric tons of kimberlite (several cubic meters of kimberlite from each of 31 pits and trenches) from the Williams 1 pipe and 27 metric tons from the Williams 4 dike. No macro-diamonds (>1 mm) or micro-diamonds (<1 mm) were recovered.

Concentrates from the Williams kimberlites contain no G10 garnets, and the Williams garnet peridotite xenoliths similarly lack G10 garnets. Temperatures and pressures estimated from mineral compositions plotted in comparison to the graphite-diamond stability boundary show that the Williams garnet peridotites overlap the graphite-diamond boundary (fig. 32; Hearn and McGee, 1984).

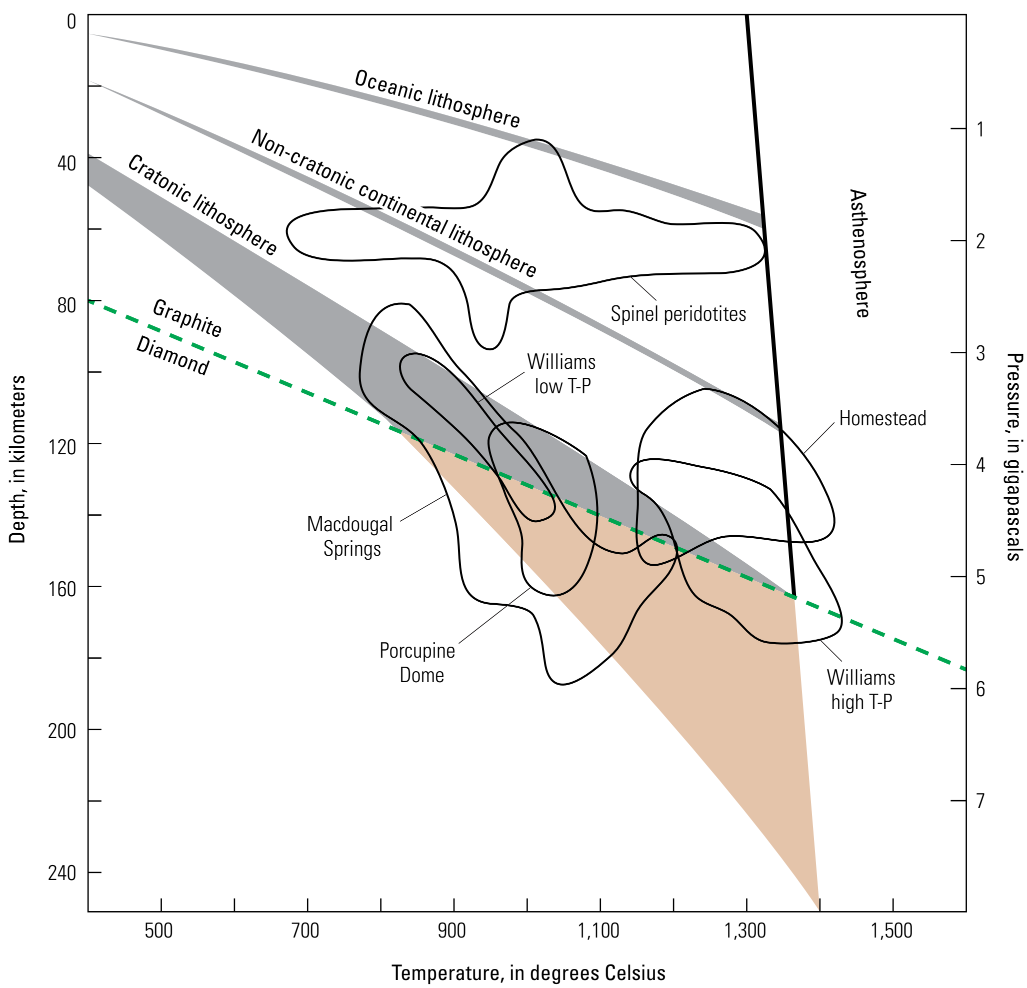


Figure 32. Diagram showing calculated and inferred pressure-temperature-depth estimates for upper mantle xenoliths from diatremes in the study area and nearby (modified from Hearn, 2004; Shirey and Shigley, 2013). T, temperature; P, pressure.

According to BLM records in 2016, 13 active lode claims cover the Williams kimberlite occurrences. They are referred to as Star of Phillips 1 to 13 (fig. 30).

Homestead Kimberlite

The Homestead kimberlite has been thoroughly evaluated by Delta Mining and Exploration. One micro-diamond was recovered in 1999 from a 45-kg sample processed in Saskatchewan Research Council Geoanalytical Laboratories (Ellsworth, 2000). In 2007, a 30.7-metric-ton bulk sample was collected from four trenches and processed in the same lab (Apex Geoscience Ltd., 2008). No macro-diamonds were recovered; the micro-diamond content was not reported (Delta Mining and Exploration Corp., 2008).

In several panned heavy-mineral concentrates from the Homestead kimberlite, ~2–12 percent of purple chromian-pyrope garnets are G10 garnets. Microprobe analyses show that 3 out of 30 analyzed Homestead garnet peridotite xenoliths contain G10 garnets (Hearn, 2004). However, those G10 garnets do not show the enriched chromium contents paired with the depleted calcium contents that are more favorable for economic diamond potential (Grütter and others, 2004). Homestead garnet peridotites plot in the graphite field (fig. 32), including the three garnet peridotites with G10 garnet compositions (Hearn, 2004).

Other Areas in the Missouri River Breaks Field

Elsewhere in or near the study area, diatremes and some stream sediments and terrace gravels have been sampled for the kimberlite indicator minerals chromian-pyrope garnet, chromian-diopside, and magnesian-ilmenite as part of a program to assess the Cow Creek Wilderness Study areas (Miller, 1986; Mytton and others, 1988). A total of 169 grab samples were collected at 8 sites (6 diatremes and 2 dikes, Miller, 1986). Chromian pyrope garnet and (or) chromian diopside were found at five of the eight sites. Twenty-five garnets from five diatremes were analyzed by electron microprobe. Only one is chromium pyrope, G9, from Saskatchewan Butte 2 diatreme; the other 24 garnets are almandines and andradites, and are not specifically kimberlite-related. No diamonds were found in the small volume of material sampled. Large-scale sampling at each site, required to test for the presence and grade of diamond, was beyond the scope of their study. One placer sample, from Coyote Coulee, contained chromium pyropes and chromium diopsides possibly derived from Williams kimberlites, although the sample site currently is topographically isolated from direct drainage from the Williams area.

Two G9 chromian pyrope garnets were found in panned concentrates from the Big Slide diatreme (Hearn and McGee, 1984). Ten purple chromium pyropes from Saskatchewan Butte 2 diatreme concentrates have been analyzed by B. Carter Hearn, Jr.; eight garnets are G9 compositions, and two are G10 compositions. No garnet peridotite xenoliths have been found in Saskatchewan Butte 2 diatreme.

The indicator mineral chromium diopside occurs in concentrates from Big Slide 1 and Squaw Creek diatremes. These two diatremes, and the Bullwhacker Coulee diatreme, contain small partly altered xenoliths of spinel peridotite, which contain chromium diopside, and, if disaggregated, can be a source of chromium diopside in concentrates. Spinel peridotite xenoliths indicate derivation from ~45 to 75 km depth, which is too shallow for diamond stability.

Undiscovered Diatremes

Undiscovered diatremes could exist in or near the study area. Aeromagnetic surveys are commonly used to locate possible kimberlites. Widely spaced aeromagnetic flight lines will only locate diatremes if the aircraft passes directly over the feature. The NURE flight line data (Hill and others, 2009) were reviewed, and five possible diatreme locations were identified (table 10). Two are within the study area but outside the proposed withdrawal area. Six of the seven diatremes that show as small positive anomalies on the higher resolution Anaconda aeromagnetic maps (Anderson and others, 2016; Anderson and Ponce, 2016) were located and mapped in the field in 1987–1991 by B. Carter Hearn Jr., on the basis of an earlier version of those maps. The seventh diatreme is totally concealed beneath Quaternary pediment gravel deposits. All seven are outside the study area.

In areas of weathered bedrock, diatremes can be positive topographic features if solid, resistant kimberlite ring dikes or plugs are present. Some diatremes show no topographic expression, and a few are negative topographic features owing to lower erosional resistance compared to the wall rocks. In areas of cover, it is unlikely that there would be any topographical indication of diatremes. About 48 percent of the study area is covered by surficial deposits, including alluvium and glacial till; surficial deposits cover about 39 percent of the proposed withdrawal area.

In aerial imagery, clues to the presence of diatremes are intricately rilled topography (in the pyroclastic fill of diatremes), light-colored areas in gray marine Bearpaw Shale, and red- or pink-colored areas of Wasatch Formation claystones and siltstones (the only red beds in the stratigraphy above the Lower Cretaceous Kootenai Formation). On-site clues are green, dark-gray, or black olivine-bearing igneous rock as float or in outcrop; green to gray soil colors (pyroclastic fill); red and green argillite pebbles (Belt Supergroup clasts from early Eocene Wasatch Formation conglomerates); pebbles of bleached syenite porphyry (from conglomerate beds in Paleocene Fort Union Formation, derived from the Little Rocky Mountains); and clasts derived from the volcanic rocks of the Bears Paw Mountains (analcime phonolite, porphyritic syenite, and tinguaite).

Table 10. Location, size, and rock type of Missouri River Breaks diatremes, major dikes, and magnetic anomalies.

[Diatremes consist of sites where fragmental deposits are the major or substantial part of intrusion; major references size and length; if rock type is not specifically known from other sources, it is called “melnoite.” na, not available]

Name	Symbol	Size (meters)	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Rock type	Notes
				Diatremes			
Baker Monument	BM	78×62	Fergus	47.6828	108.9750	“melnoite”	
Barnard Ridge	BR	190×120	Blaine	47.8203	109.2455	“melnoite”	
Beauchamp Creek	BC	73×46	Phillips	47.8797	108.4147	“melnoite”	
Bergum	BE	225×155	Fergus	47.6894	109.2889	“melnoite”	
Big Slide 1	BS1	170×135	Blaine	47.8303	109.2678	“melnoite”	Chromian pyrope garnet and chromian diopside occur in concentrates from Big Slide 1 diatreme (Hearn and McGee, 1984). Two grains of G9 garnet were analyzed. Sparse, small, partly altered spinel dunite and harzburgite xenoliths occur in east breccia pipe in Big Slide 1 diatreme.
Big Slide 2	BS2	75×30	Blaine	47.8297	109.2700	“melnoite”	
Bird Rapids 1 northeast	BR1	160×30	Fergus	47.7630	109.1842	“melnoite”	
Bird Rapids 2 southwest	BR2	76×37	Fergus	47.7619	109.1869	“melnoite”	
Black Butte 1	BB1	270×210	Blaine	47.8428	109.1769	Bedded pyroclastic deposits; central breccia; plug of melnoite	
Black Butte 2 north	BB2	21×18	Blaine	47.8953	109.1783	“melnoite”	
Black Butte 3 southwest	BB3	150×67	Blaine	47.8397	109.1805	“melnoite”	
Black Rock	BR	145×115	Blaine	47.8558	109.0472	“melnoite”	
Boundary	BO	180×120	Blaine	47.9255	108.8855	“melnoite”	
Bullwhacker Coulee	BU	330×240	Blaine	47.8078	109.0275	“melnoite”	
Burnt Wagon	BW	115×61	Blaine	47.8955	108.9669	“melnoite”	
Button Butte	BB	90×40	Fergus	47.5036	108.5050	“melnoite”	
Cabin Creek	C	49×47	Phillips	47.8914	108.8061	“melnoite”	
Cole	CO	420×200	Blaine	47.9361	108.8597	“melnoite”	
Crazyman Coulee	CC	100×80	Blaine	47.9692	108.8272	“melnoite”	
Ervin Ridge 1	E1	200×200	Blaine	47.8175	109.1250	“melnoite”	
Ervin Ridge 2 southwest	E2	40×30	Blaine	47.8150	109.1286	“melnoite”	
Gilmore	G	130×90	Blaine	47.8633	109.0033	“melnoite”	
Hay Coulee	H	230×205	Blaine	47.9128	108.9586	“melnoite”	Studied by Miller (1986). Referred to as HAL 21, 22 claims.

Table 10. Location, size, and rock type of Missouri River Breaks diatremes, major dikes, and magnetic anomalies.—Continued

[Diatremes consist of sites where fragmental deposits are the major or substantial part of intrusion; major references size and length; if rock type is not specifically known from other sources, it is called "melnoite." na, not available]

Name	Symbol	Size (meters)	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Rock type	Notes
Haystack Butte	HA	75×60	Chouteau	47.6372	110.2222	"melnoite"	
Joslin Bench	JB	200×170	Phillips	47.8828	108.8069	"melnoite"	
Lieurance 1	L1	395×240	Phillips	47.8939	108.8778	"melnoite"	
Lieurance 2 east	L2	69×40	Phillips	47.8639	108.8786	"melnoite"	
Lieurance 3 west	L3	280×120	Blaine	47.8900	108.8936	"melnoite"	
Lone Tree Ridge	LT	375×280	Blaine	47.8317	109.2164	"melnoite"	
Macdougal Springs	MD	290×190	Blaine	47.9344	108.9200	Pyroclastic tuff deposits; 4 breccia units; 2 aillikite intrusions. Irving and Hearn (2003).	Macdougal Springs diatreme has garnet peridotite xenoliths (and spinel, and spinel-garnet peridotites; nearly all xenoliths are partly altered with olivine and orthopyroxene altered to calcite and quartz).
Miller Coulee	MI	150×150	Phillips	47.9139	108.8064	"melnoite"	
Saskatchewan Butte 1	SB1	280×245	Phillips	47.8622	108.8333	"melnoite"	Studied by Miller (1986). Referred to as HAL 1 claim.
Saskatchewan Butte 2	SB2	130×33	Phillips	47.8608	108.8236	"melnoite"	Studied by Miller (1986). Referred to as HAL 40 claim. Chromian pyrope garnet and chromian diopside occur in concentrates. Ten chromian pyropes from Saskatchewan Butte 2 were analyzed by B. Carter Hearn Jr. Eight have G9 compositions and two have G10 compositions.
Shellenberger	SH	520×285	Blaine	47.8319	108.9008	"melnoite"	Studied by Miller (1986). Referred to as HAL 2, 3 claims.
Squaw Creek	SC	550×200	Blaine	47.8955	108.9180	"melnoite"	Studied by Miller (1986). Referred to as HAL 23, 24 claims. Sparse, small, partly altered spinel dunite and harzburgite xenoliths occur in small dikes in Squaw Creek diatreme.
Sturgeon 1 west	S1	95×88	Blaine	47.8078	109.0725	"melnoite"	
Sturgeon 2 central	S2	160×105	Blaine	47.8100	109.0678	"melnoite"	
Sturgeon 3 east	S3	325×185	Blaine	47.8108	109.0630	"melnoite"	
Sturgeon 4 NE	S4	up to 60×30	Blaine	47.8069	109.0494	"melnoite"	Several
Tick	T	235×130	Blaine	47.8597	109.2428	"melnoite"	
Williams 1	W1	350×250	Phillips	47.8508	108.6925	kimberlite (Hearn and McGee, 1984; Irving and Hearn, 2003)	Concentrates and garnet peridotite xenoliths from the Williams kimberlites contain no G10 garnets.

Table 10. Location, size, and rock type of Missouri River Breaks diatremes, major dikes, and magnetic anomalies.—Continued

[Diatremes consist of sites where fragmental deposits are the major or substantial part of intrusion; major references size and length; if rock type is not specifically known from other sources, it is called "melnoite." na, not available]

Name	Symbol	Size (meters)	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Rock type	Notes
Williams 2 northeast	W2	120×40	Phillips	47.8578	108.6900	kimberlite (Hearn and McGee, 1984; Irving and Hearn, 2003)	Concentrates and garnet peridotite xenoliths from the Williams kimberlites contain no G10 garnets.
Williams 3 west	W3	34×28	Phillips	47.8522	108.6947	kimberlite (Hearn and McGee, 1984; Irving and Hearn, 2003)	Concentrates and garnet peridotite xenoliths from the Williams kimberlites contain no G10 garnets.
Williams 4 dike	W4	390×37	Phillips	47.8525	108.7030	kimberlite (Hearn and McGee, 1984; Irving and Hearn, 2003)	Concentrates and garnet peridotite xenoliths from the Williams kimberlites contain no G10 garnets.
Major or unusual dikes and plugs							
Barnard Ridge northeast 1	BRd1	480	Blaine	47.8222	109.2422	"melnoite"	
Barnard Ridge northeast 2	BRd2	500	Blaine	47.8242	109.2361	"melnoite"	
Big Slide NE	BSd	240	Blaine	47.8333	109.2583	carbonatite	
Bird Rapids	BRd	4160	Blaine	47.7958	109.1472	"melnoite"	
Lion Coulee	LCd	1170	Blaine	47.8522	109.1633	"melnoite"	
Black Butte south	BBsd	450	Blaine	47.8389	109.1786	"melnoite"	
Bull Creek	BCd	480	Phillips	47.8705	108.7372	carbonatite	
Bullwhacker Coulee	BUd1	3310	Blaine	47.8278	109.0917	"melnoite"	Discontinuous
Bullwhacker Coulee north	BUd2	880	Blaine	47.8467	109.0722	"melnoite"	
Bullwhacker diatreme SW	BUd3	800	Blaine	47.8055	109.0319	"melnoite"	
Burnt Wagon	BWd	2610	Blaine	47.8789	108.9842	"melnoite"	
Castle Rock	CRd	400	Blaine	47.8633	108.9000	"melnoite"	Several (~8) features; Studied by Miller (1986).
Ervin Ridge south 1	Esd1	850	Blaine	47.8133	109.1361	carbonatite	
Ervin Ridge south 2	Esd2	220	Blaine	47.8103	109.1397	alnöite	
Ervin Ridge north	End	500	Blaine	47.8230	109.1347	carbonatite	
Gilmore north 1	Gd1	880	Blaine	47.8667	109.0055	"melnoite"	

Table 10. Location, size, and rock type of Missouri River Breaks diatremes, major dikes, and magnetic anomalies.—Continued

[Diatremes consist of sites where fragmental deposits are the major or substantial part of intrusion; major references size and length; if rock type is not specifically known from other sources, it is called "melnoite." na, not available]

Name	Symbol	Size (meters)	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Rock type	Notes
Gilmore west 2	Gd2	250	Blaine	47.8628	109.0055	"melnoite"	
Gilmore east 3	Gd3	480	Blaine	47.8636	108.9992	"melnoite"	
Gilmore east arcuate 4	Gd4	950	Blaine	47.8653	109.0005	"melnoite"	
Lone Tree Ridge NE	LTd	600	Blaine	47.8403	109.2103	"melnoite"	
Miller Coulee	MId	620	Phillips	47.9111	108.8033	carbonatite	
Mud Creek 1 NE	M2	up to 21×9	Phillips	47.8847	108.6569	"melnoite"	5 plugs
Mud Creek 1 SW	M1	24×7	Phillips	47.8828	108.6594	"melnoite"	Sill, plug
Ricker Butte	R	up to 200×12	Phillips	47.8819	108.3750	alnöite (Irving and Hearn, 2003)	4 sills/dikes
Shellenberger Divide	SDd	210	Blaine	47.8433	108.8717	carbonatite	Studied by Miller (1986).
Sturgeon Island	Sd	930	Blaine	47.8000	109.0917	"melnoite"	Discontinuous
Thorsen	THd	350	Phillips	47.8944	108.7730	"melnoite"	
Winifred East	WEd	1470	Fergus	47.5808	109.1625	"melnoite"	Zone
Zortman 1 east	Z1p	335×75	Phillips	47.9144	108.5172	alnöite (Irving and Hearn, 2003)	Plug
Zortman 2 west	Z2p	21×12	Phillips	47.9130	108.5244	alnöite	Plug
Anomalous features							
Hidden	HI	250–400	Blaine	47.9394	108.7744		Magnetic anomaly on Anaconda aeromagnetic survey; probable diatreme; estimated size based on anomalies over mapped diatremes.
na	na	na	Blaine	47.9671	108.8576		Anomaly on Anaconda aeromagnetic survey
na	na	na	Blaine	47.9784	108.8369		Anomaly on Anaconda aeromagnetic survey
na	na	na	Phillips	47.9066	108.7869		Anomaly on Anaconda aeromagnetic survey
na	na	na	Phillips	47.8778	108.8269		Anomaly on Anaconda aeromagnetic survey
na	na	na	Blaine	47.8316	108.9642		Anomaly on Anaconda aeromagnetic survey
na	na	na	Phillips	47.8667	108.7000		Anomaly on Anaconda aeromagnetic survey. Ground magnetic survey shows 90 gamma positive anomaly, unknown source. No igneous rock, no diatreme fill, no baking of Cretaceous bedrock.
na	na	na	Blaine	47.8057	109.0174		Aeromagnetic spike on NURE flight line
na	na	na	Fergus	47.7189	109.0011		Aeromagnetic spike on NURE flight line
Connoly Coulee	na	na	Petroleum	47.3656	108.2744		Baked sandstone anomaly

Potential for Occurrence

The study area includes part of the Missouri River Breaks field, so the study area was assessed for diamond (Tracts MTD01 through MTD03, appendix 2; fig. 33; San Juan and others, 2016). For this assessment, the rank of mineral potential is based on the regional geologic setting, the occurrence of the appropriate rock type (kimberlite or lamproite), the presence of diamond, the presence of indicator minerals that are consistent with the kimberlitic magma cutting upper mantle rocks that are within the diamond stability field, and the global rarity of diamond in known pipes (appendix 2).

Nearly all diamond-bearing kimberlites and lamproites occur in regions above Archean cratons ("Clifford's Rule", as modified by Janse, 1994). Known diatremes in the study area occur above the sections of the GFTZ that contains 1.8–1.7 Ga crust, which was derived from addition of igneous material or from metamorphic re-equilibration of Archean terrane in that zone (Peterman, 1981; Carlson and others, 2004; Sims and others, 2004; Gifford, 2010; Barnhart and others, 2012). Using the southeastern boundary of the GFTZ as shown in Barnhart and others (2012), both the Williams kimberlite cluster and the Homestead kimberlite lie above the GFTZ (fig. 3*A*), a Paleoproterozoic suture zone between two Archean terranes—Wyoming and Medicine Hat. The suturing event may have affected the cratonic root beneath the Archean cratons, reducing the potential for diamond occurrence and diamond survival.

Other parts of the study area that overlie the Wyoming Craton basement could have been more favorable for diamond, if kimberlite or lamproite magmas had been available for rapid transport. The Smoky Butte lamproite, south of the study area (fig. 3*B*), is not an olivine-rich lamproite, which would be more favorable for diamond occurrence. The history of diamond evaluation for Smoky Butte is unknown to the authors.

One kimberlite cluster (Williams) occurs in the study area; no macro-diamonds were found in commercial processing of 312 metric tons of kimberlite. One kimberlite (Homestead) occurs in the Grassrange area, 35 km south of the study area; one micro-diamond was recovered in early exploration, but later commercial processing of 30 metric tons of kimberlite found no macro-diamonds.

Group 9 chromian-pyrope garnets occur in garnet peridotite xenoliths and in heavy-mineral concentrates from Williams kimberlites. Group 10 chromian-pyrope garnets favorable for diamond occurrence are lacking. The Homestead kimberlite contains 2 to 12 percent G10 garnets in the garnet population in heavy-mineral concentrates, and 3 of 30 xenoliths sampled contain G10 garnets; these G10 garnets do not have the more enriched chromium contents and depleted calcium contents that would be favorable for diamond occurrence. The calculated equilibrium temperature-pressure field for Williams, Homestead, and Macdougal Springs garnet peridotite xenoliths overlaps the graphite-diamond stability boundary. However, xenolith temperature-pressure conditions are not definitive for prediction of diamond association. Macdougal Springs data may be less accurate because the xenoliths are partially altered, and the former presence of orthopyroxene is assumed.

Taken together, all available data indicate that the diamond potential of the study area is low. Tract delineation is based on the tendency of diatremes and related rocks to occur in clusters. We used the distances between intrusions and intrusion density to create mineral potential tracts. As described in Hammarstrom and Zientek (2016), two Esri ArcGIS tools were used to construct the tracts (fig. 33): (1) the "Generate Near Table" tool (to compute the "maximum near distance"), and (2) the "Kernel Density" tool.

First, the distance between the centers (centroids) of every diatreme were determined using ArcMap's "Generate Near Table" tool. The greatest near-distance is 70.3 km between two diatremes, and we used this value as the radius from which to draw a boundary (buffer) around all the known diatremes. This boundary forms the outer extent of the tract with the lowest level of confidence (B), which is tract MTD01 (fig. 33; appendix 2; San Juan and others, 2016). Second, in order to map areas with certainty levels C and D, the kernel density surface (a raster file) was created in ArcGIS and classified into three groups using a geometrical interval classification scheme. The boundary between the D and C certainty levels ranges from 2,510 m to 5,235 m to the center of the nearest diatreme, and the boundary between the C and B certainty levels ranges from 3,616 m to 8,291 m to the center of the nearest diatreme (fig. 33; appendix 2; San Juan and others, 2016).

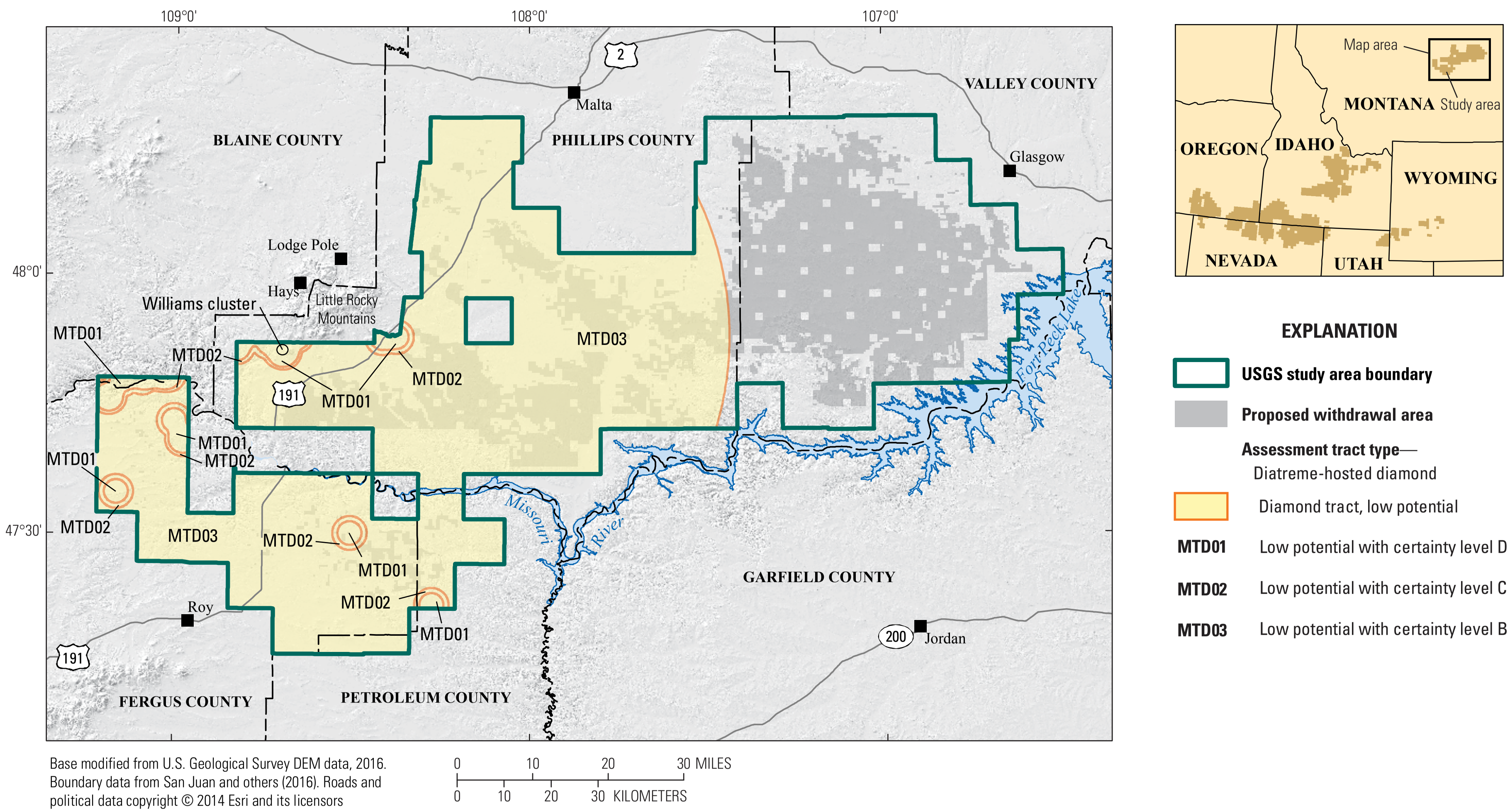
Both this study and the Utah-Wyoming study (Wilson and others, 2016) assessed diamond potential. There are other methods and approaches that could be used to create the tract maps and different parameters could be selected for this procedure. The reason for using this approach was for consistency in representing mineral potential tracts for the same deposit type between different areas.

Diamond Deposits Tracts: MTD01 (Diamond 1), MTD02 (Diamond 2), and MTD03 (Diamond 3)

These are low-potential tracts for diamond deposits, with certainty levels of D, C, and B, respectively. Parts of these tracts overlie areas that are specifically proposed for withdrawal.

Economic Analysis of the Deposit Types

Kimberlite-hosted diamond deposits in diatremes and dikes are one of the two main sources of diamonds from hard rock mines. However, in the study area, the lack of any past production, the absence of macro-diamonds, the scarcity of kimberlite, the lack of G10 garnets that are enriched in chromium and depleted in calcium, and the young age of the basement terrane all suggest that the potential for diamond deposits in the study area is low. There are no known kimberlites in the proposed withdrawal area, so the potential for diamond deposits in the proposed withdrawal area is also low.



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 33. Mineral potential map for diamond deposits in the North-Central Montana Sagebrush Focal Area. USGS, U.S. Geological Survey.

Salable Minerals

Salable minerals, also known as mineral materials, include common varieties of sand, gravel, decorative stone, dimension stone, pumice, clay, and rock (appendix 1 in Day and others, 2016). These materials are typically used in various construction, agriculture, and decorative building or landscaping applications. Management of salable minerals in the planning area must comply with the Mineral Materials Act of 1947 (30 U.S.C. 601 et seq.), and all other relevant Federal and State laws.

In the study area, the most important salable minerals are sand and gravel. There has also been evaluation of clay. There has been no known production of decorative stone, dimension stone, pumice, or rock, and there are no known sources for these materials.

Sand and Gravel

The March 6, 2016, BLM LR2000 database shows one approved site for sand and gravel in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area (table 11).

Table 11. Active Bureau of Land Management mineral material authorizations in the proposed withdrawal area within the North-Central Montana Sagebrush Focal Area.

[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]

Commodity	Number of approved sites	Number of pending sites
Sand and gravel	1	0

Sand and gravel have been produced from several locations within the study area (fig. 34). Most sand and gravel are used for construction purposes, and the majority is used for aggregate. This usage requires materials that are hard, durable, chemically nonreactive, and low in alkalis, and that do not contain deleterious minerals such as swelling clays. Because transport is typically the most substantial cost in producing aggregate, the source of the materials must be close to where they are needed.

The Bearpaw Shale, Judith River Formation, and Claggett Shale, which cover the majority of the study area, are not viable sources for aggregate because their rocks are soft, not durable, and commonly contain bentonite. Consequently, sand and gravel in the study area have been produced from glacial deposits and from alluvial deposits, where harder rocks and minerals are selectively preserved, and deleterious clay minerals are winnowed out (fig. 35).

The National Minerals Information Center of the USGS has confirmed that sand and gravel have been produced from operations in Fergus, Phillips, and Valley counties, and crushed stone has been produced from Fergus County. However, specific production figures are withheld to avoid disclosing company proprietary data, and the listed operations do not lie within the study area. No sand and gravel production was listed for Petroleum County.

Locations of active mines within the Focal Area were compiled from the Montana Department of Environmental Quality Opencut Mining Program permit data (Fernette, Bellora, and others, 2016; Fernette, Schweitzer, and Sangine, 2016). There are a total of 18 active mines within the proposed withdrawal area, and 15 of these are sand and gravel operations (Fernette, Bellora, and others, 2016; Fernette, Schweitzer, and Sangine, 2016).

In some places outside the study area, the Late Cretaceous Fox Hills and Hell Creek Formations contain friable sandstones that are a source of sand. These formations have been quarried, crushed, and mixed with asphalt for use as paving material on highways (Johnson and Smith, 1964).

Clay Minerals

Clay minerals considered here include kaolinite and common clay; bentonite in the study area is described and discussed in the locatable minerals section of this report.

Common clay accounts for most of the world clay production, but not its value. In most places, common clay is a mixture of clay minerals. Common clay is used to manufacture brick, drain and roof tile, sewer pipe, and other construction materials. Common clay deposits are typically derived from shales that are low in iron and calcium.

Kaolinite is a clay mineral with the chemical composition $Al_2Si_2O_5(OH)_4$. Kaolinite is used as (1) a filler and coater in paper, rubber, paint, and food; (2) the main component in refractories and fine china; and (3) a catalyst in petroleum refining and other manufacturing processes.

There are no verified records of production of kaolinite or common clay from the study area. Two studies suggest that kaolinite may occur in the study area, but the potential for significant deposits is low. Sahinen and others (1958) sampled and analyzed pure white kaolinite in 5- to 30-cm-thick beds of the Ellis Formation on the south side of the Little Rocky Mountains in sec. 12, T. 24 N., R. 24 E. This is white, highly refractory clay, with fair plasticity and green strength. The amount of kaolinite at this locality is not large (Sahinen and others, 1958).

Elsewhere in the study area, the Colgate Member of the Fox Hills Formation is a kaolinitic sandstone that is a potential source of kaolinite. The Whitemud Formation in Saskatchewan is the lateral equivalent of the Fox Hills Formation. The suitability of the Whitemud Formation as a source of kaolinite for paper coating was evaluated, and Pruett (1988) concluded that the economics were questionable because the kaolinite from the Whitemud has high abrasivity that prevents use in paper products, the yield of kaolinite from the Whitemud was low, and the kaolinite quality varies within the Whitemud.

Further work on the kaolinite in the Fox Hills Formation may be warranted, but results from the Whitemud Formation are not encouraging, and there are no known records of production of kaolinite from within the study area.

Gemstones: Petrified Wood

Petrified wood locally occurs in the Paleocene Fort Union Formation, in the Cretaceous sedimentary rocks of the upper part of the Judith River Formation, and in the Hell Creek Formation. However, the petrified wood is fairly drab; light tan, gray, or white; white-weathering; and incompletely petrified, with black carbonaceous areas. Locally, the petrified wood can have fine-grained drusy quartz coatings on fractures. The petrified wood in the bedrock of the study area is not at all similar to the multi-colored petrified wood from Arizona and southwest Montana (B. Carter Hearn, Jr., written commun., 2016).

The southern part of the study area contains a locality outside the proposed withdrawal area that is listed in the BLM database as "expired: non-precious gemstone". Comparison of the location to the geologic map suggests that this corresponds to an occurrence of petrified wood in the Hell Creek Formation. Given the overall quality of petrified wood in the study area, the lack of other claims in the area, and the absence of previous assessments or citations in the published literature (Parks and others, 2016a, b), it seems unlikely that there are significant resources of gem-quality petrified wood in the study area.

Mineral Economics

Strategic and Critical Mineral Materials

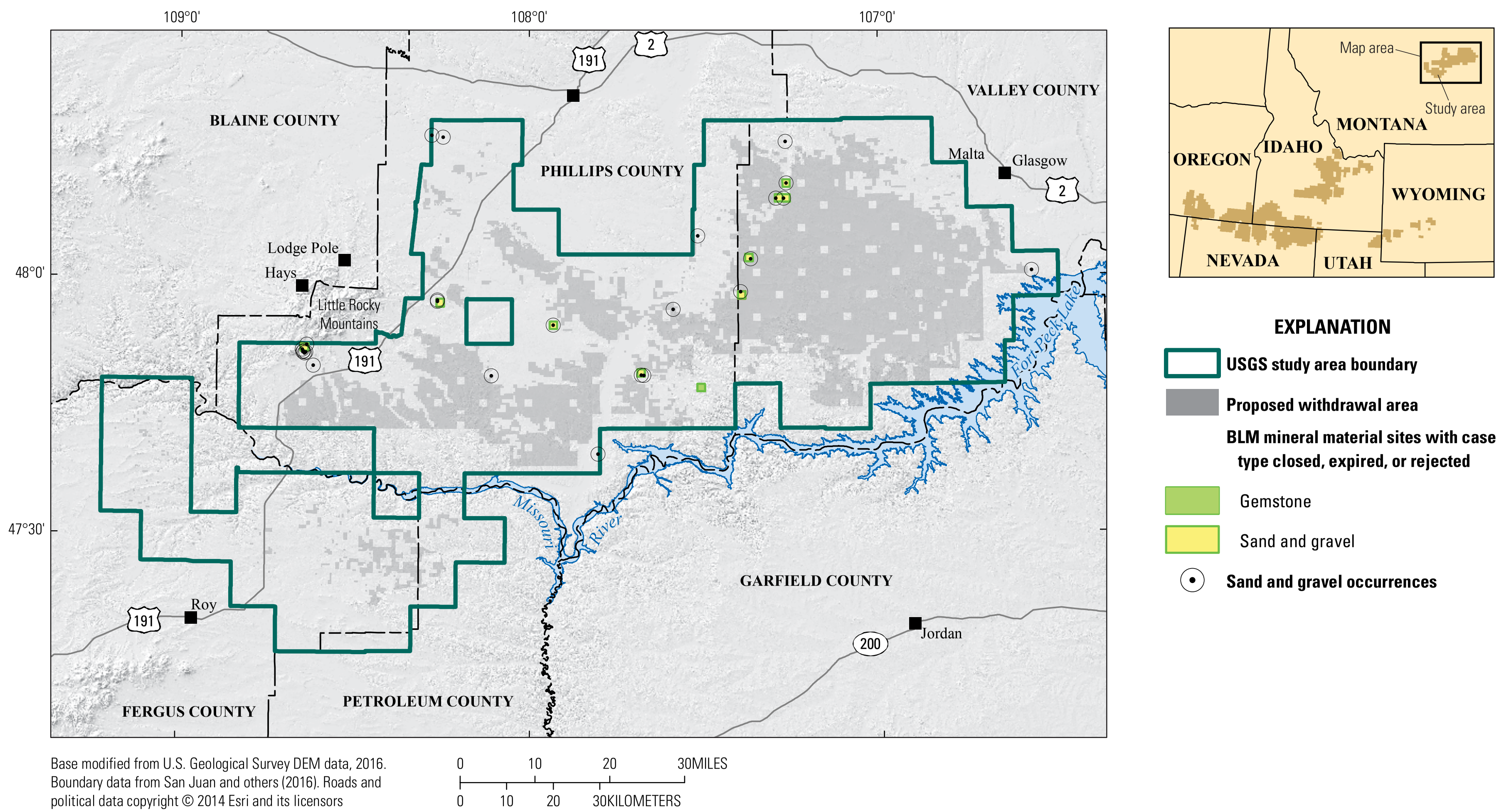
As described and discussed elsewhere, the locatable minerals considered for the North-Central Montana Sagebrush Focal Area are gold, silver, bentonite, and diamond. None of these are considered to be strategic or critical minerals (British Geological Survey, 2012; appendix 4 in Day and others, 2016).

Outside the study area, including localities in the Bears Paw Mountains and on the Rocky Boy's Reservation, carbonatites of the Central Montana alkaline province have been examined for REE potential, (Pecora, 1963; Lindsey and others, 1977; McNary, 1981). On a global basis, carbonatites are the preeminent host rock for REE deposits, including the Bayan Obo deposit in China, which is currently the largest REE deposit worldwide (Yang and others, 2011; Chakhmouradian and Zaitsev, 2012).

We did not evaluate the likelihood of REE deposits in the study area for the following reasons:

1. In the Little Rocky Mountains, which are outside the study area, carbonatites are a minor component of the igneous rock suite.
2. The only known igneous rocks that crop out in the study area are syenite and alkali ultramafic rocks in the Missouri Breaks diatremes, and neither rock type is a favored host for REE deposits.
3. The only igneous rocks that crop out in the proposed withdrawal area are part of the Missouri River Breaks diatreme complex, and these bodies are too small to host a large REE deposit.
4. As expected for alkaline igneous rocks, available geochemical data show REE enrichment in many of the igneous rocks that were collected in the study area, but none of these samples contain strongly anomalous concentrations of REEs (Smith and others, 2016).
5. There has been no production of REEs from the study area, to the best of our knowledge there has been no extensive prospecting for REE deposits, and there are no previous assessments for REEs in the study area (Parks and others, 2016a, b).

Taken together, these factors indicate that the potential for REE deposits in the study area is low.



Base modified from U.S. Geological Survey DEM data, 2016.
Boundary data from San Juan and others (2016). Roads and political data copyright © 2014 Esri and its licensors
USA Contiguous Albers Equal Area Conic Projection. Central meridian, 108° W., latitude of origin, 36.5° N. North American Datum of 1983

Figure 34. Map showing known deposits of salable minerals and active mineral material permit sites in the North-Central Montana Sagebrush Focal Area (modified from Dicken and San Juan, 2016a, b; Fernette, Bellora, and others, 2016; Fernette, Schweitzer, and Sangine, 2016). BLM, Bureau of Land Management; USGS, U.S. Geological Survey.

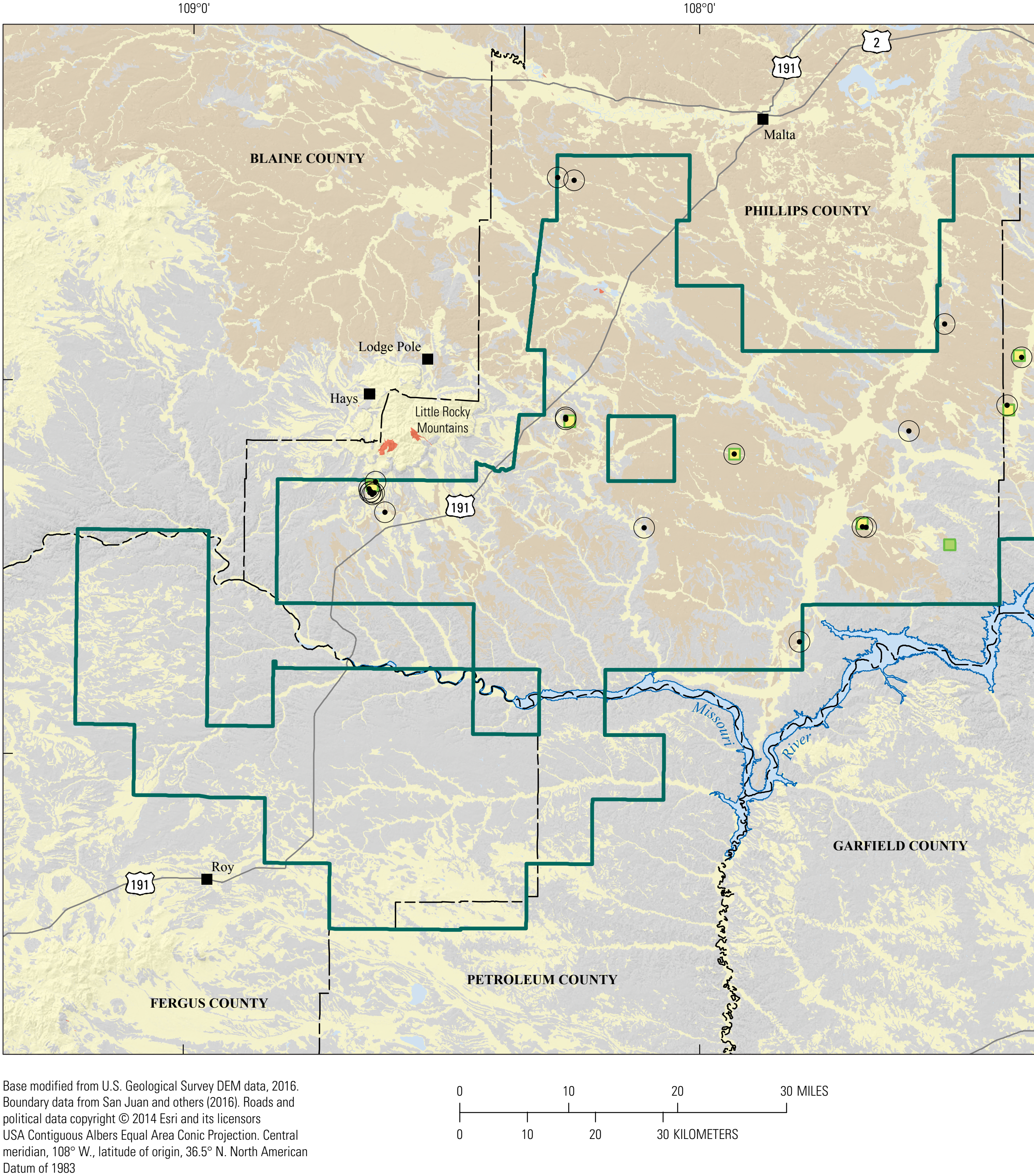
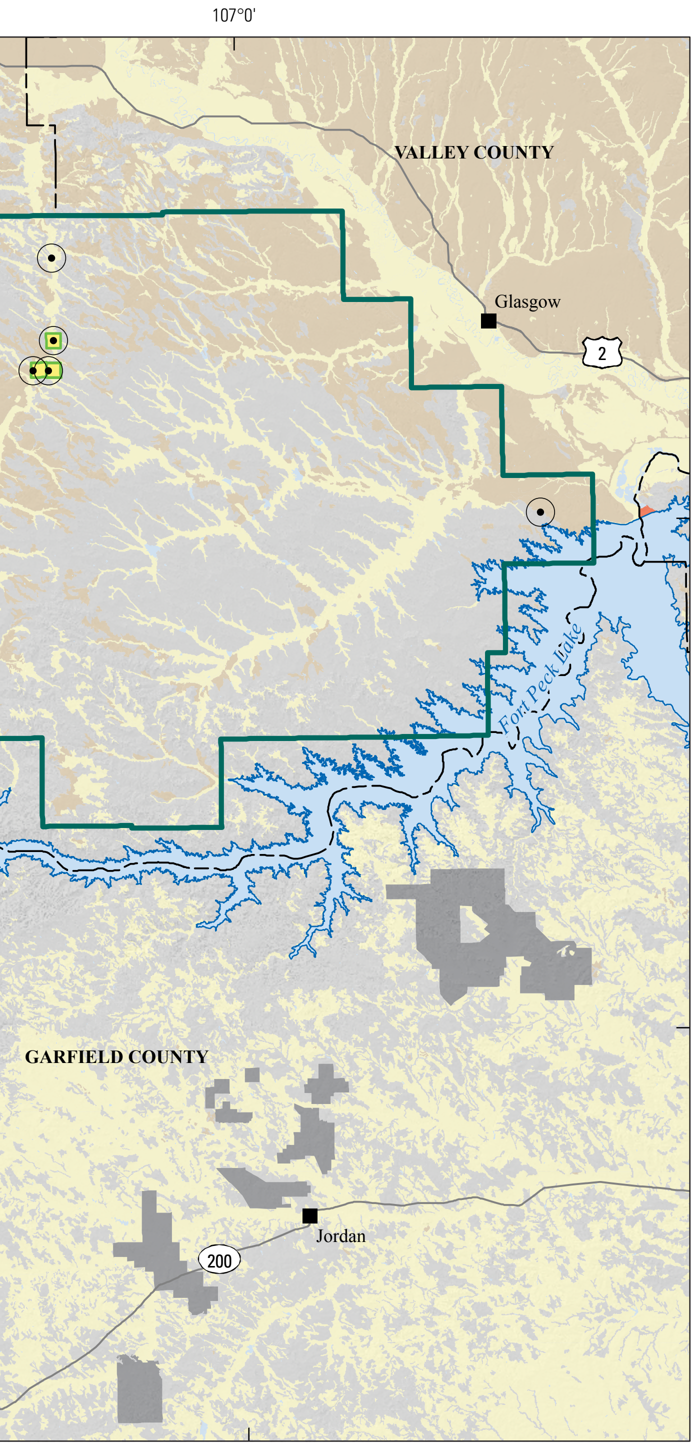
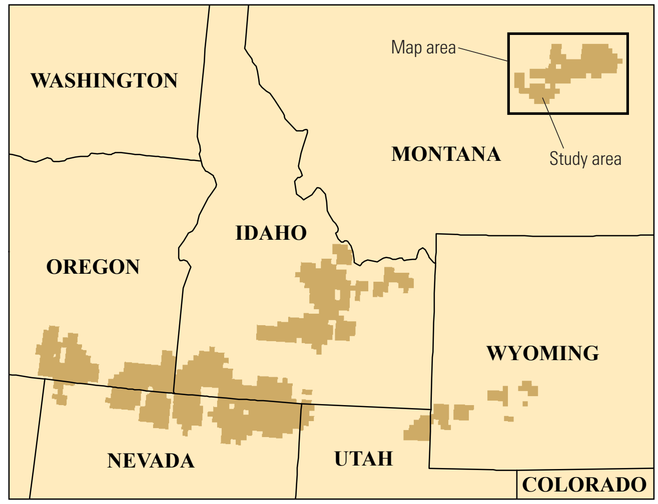


Figure 35. Map showing known sand and gravel deposits, active mineral material permit sites, and surficial deposits in the North-Central Montana Sagebrush Focal Area (modified from Dicken and San Juan, 2016a, b; Fernette, Bellora and others, 2016; Fernette, Schweitzer, and Sangine, 2016; Montana State Library, 2016b). BLM, Bureau of Land Management; USGS, U.S. Geological Survey.





EXPLANATION

- **USGS study area boundary**
- **BLM mineral material sites with case type closed, expired, or rejected**
  - Gemstone
  - Sand and gravel
- **Alluvium or colluvium**
- **Till, eolian deposits, glacial outwash, or glaciolacustrine deposits**
- **Residuum**
- **Denied access**
- **Man made feature**
- **Sand and gravel occurrences**

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Appendixes 1–4

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.

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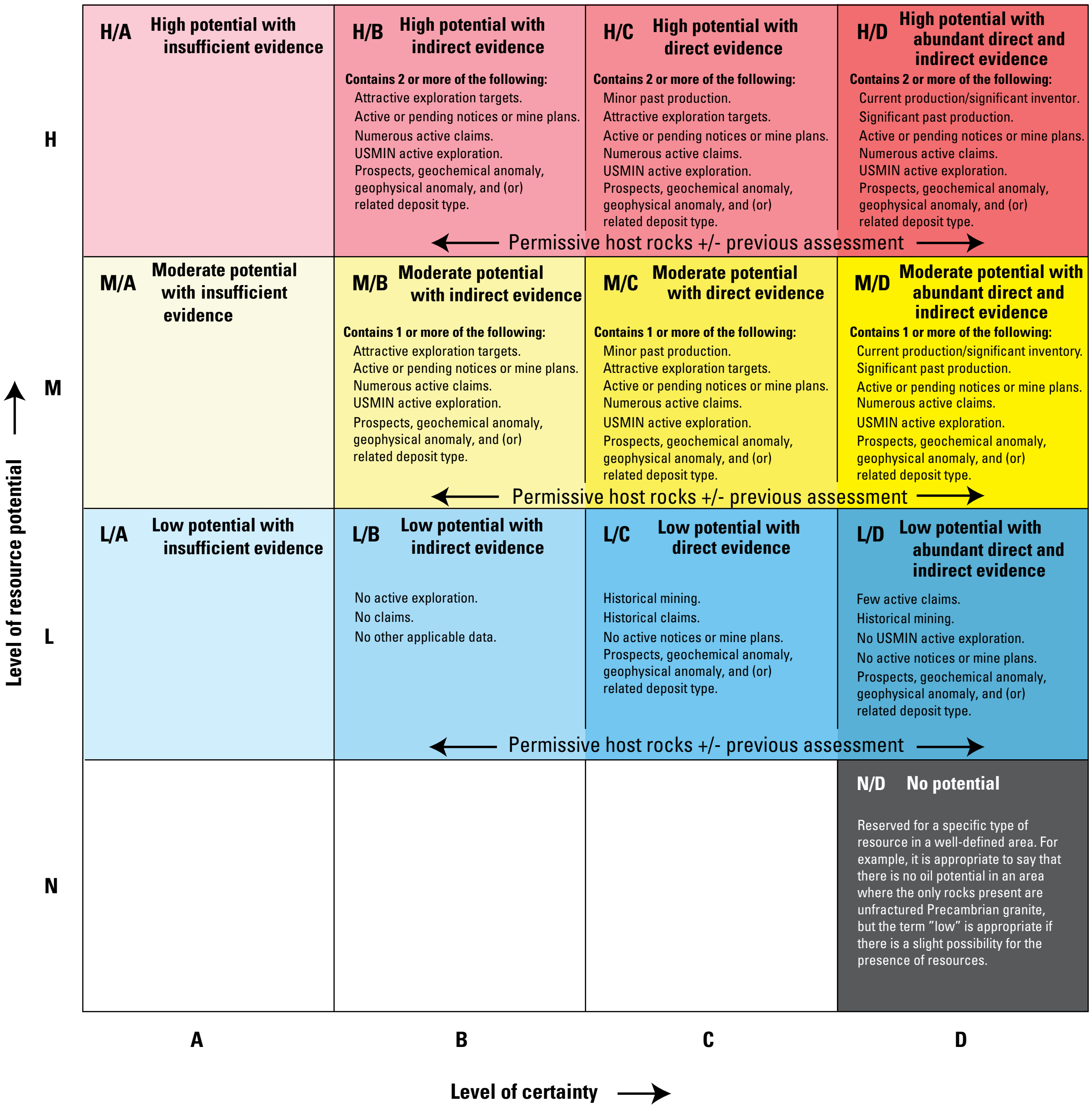

Figure 1-1. Matrix showing the classification system used for qualitative mineral-resource potential for locatable minerals in the Sagebrush Mineral-Resource Assessment (see text for abbreviations).

Appendix 2. Mineral-Potential Assessment Tracts for Locatable Minerals in the North-Central Montana Sagebrush Focal Area

This appendix is available online only as an Excel (.xlsx) table at http://dx.doi.org/10.3133/sir20165089D. The table lists mineral-potential assessment tracts for locatable minerals in the North-Central Montana Sagebrush Focal Area. San Juan and others (2016) provide a geographic information system (GIS) database that shows the tracts that are included within this report.

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Appendix 3. Oil and Gas Plays and Assessment Units in the North-Central Montana Sagebrush Focal Area

This appendix is available online only as an Excel (.xlsx) table at http://dx.doi.org/10.3133/sir20165089D. 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 North-Central Montana Sagebrush Focal Area. 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 4. Parameters for the Geostatistical Model of the Lower Contact of the Upper Y Bentonite Bed in the Malta and Glasgow Areas, Montana

A geostatistical model representing the base of the Y bentonite bed was created using the Geostatistical Analyst tool in Esri ArcGIS 10.3.1 for desktop. The input for the model was point data representing the elevation of the base of the bed based on interpretation of satellite imagery. In areas where the Bearpaw Shale is exposed, large concretions occurring along the base of the Y bentonite bed were mapped by a geologist using satellite imagery. Using GIS software, the geologist digitized the distribution of concretions as short line segments directly from the satellite images. The line segments represent one or more concretions along the base of the bed. The line file segments were converted to points and an elevation for the point was extracted from a 30-m digital elevation model. These points were the input for the geostatistical model.

In ArcGIS, the geostatistical model for the base of the Y bed was created using empirical Bayesian kriging. The number of points in the input dataset and the model parameters are summarized in table A1. Both a prediction surface and a prediction standard error map were created.

Table 4-1. Parameters used in creating the geostatistical model for the lower contact of the Y bentonite bed in the Malta and Glasgow areas, Montana.

Item	Malta area	Glasgow area
Number of records in point feature class	1,035	799
Data field	Elevation, feet	Elevation, feet
Tool	Geostatistical Analyst, geostatistical wizard	Geostatistical Analyst, geostatistical wizard
Method	Empirical Bayesian Kriging	Empirical Bayesian Kriging
Output types	Prediction Prediction standard error map	Prediction Prediction standard error map
Transformation type	None	None
Semivariogram model type	Power	Power
Subset size	50	50
Overlap factor	3	2
Number of simulations	100	100
Searching neighborhood	Standard circular	Standard circular
Neighbors to include	15	15
Include at least	10	10
Sector type	Full	Full
Radius	248.166966768327	181.373355827947
Angle	0	0
Mean standardized (should be close to zero)	0.003239687619914229	0.016799063853327953
Root-mean-square standardized (should be close to one)	0.940889424436895	0.9325571467441592

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