METALLIC ORE DEPOSITS OF MONTANA

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INTRODUCTION

Montana, the "Treasure State," has a rich history of placer and hard rock mining for metallic commodities. It contains two world-class ore bodies, Butte and Stillwater, and hundreds of smaller deposits that have been mined from the 1870s to the present day. The purpose of this chapter is to give an overview of the metallic mineral deposits of Montana excluding the Butte and Stillwater mines, which are the focus of papers elsewhere in this volume. Included under the category of "metallic deposits" are concentrations of base metals (Cu, Pb, Zn), precious metals (Au, Ag, Pt, Pd), iron and ferro-alloy elements (e.g., Fe, Mo, Co, Cr), rare-earth elements, uranium, thorium, and a few other rare metals of economic importance. In the 1960s, the U.S. Geological Survey (USGS) and Montana Bureau of Mines and Geology (MBMG) compiled a review of the metallic and industrial mineral mines and resources of Montana (MBMG Special Publication 28, 1963), and organized their compilation by commodity. The current paper takes a different approach. Deposits are discussed partly by geologic time (beginning in the Archean) and partly by ore-deposit type. This is not the order in which the various mines were discovered and exploited by prospectors. Indeed, the first mineral deposits to draw miners to Montana were placer gold deposits in Tertiary or Quaternary gravels. The oldest mineral deposits of Montana, such as Stillwater and the Cu-Ag mines near Troy, would not see large-scale mining until the mid-20th century.

There have been thousands of papers, reports, and student theses on the individual deposits and mining districts in Montana. This review does not come close to citing all of them, although effort has been made to cite most of the principal sources that discuss the geology and ore-forming characteristics of the different deposit types. In citing the literature, emphasis has been placed on more recent work published after MBMG Special Publication 28.

ARCHEAN AND PALEOPROTEROZOIC DEPOSITS

Stillwater Complex

Metamorphic rocks of Archean and/or Paleoproterozoic age crop out extensively on the Beartooth Plateau, and form the backbone of several mountain ranges in southwest Montana, including the Ruby, Highland, Tobacco Root, Gravelly, and Madison ranges. By far the most significant metal deposits that date to this time period are found in the Stillwater Complex, a 2.7 Ga layered mafic/ultramafic intrusion exposed on the north flank of the Beartooth Mountains. As discussed in another chapter of this volume (Boudreau and others, 2020), the Stillwater Complex contains some of the world's richest deposits of platinum-group elements in the thin but laterally extensive J-M Reef (the target of the active Stillwater and East Boulder underground mines), extensive layers of chromite (mined by Anaconda in WWI and WWII), and scattered bodies of Cu- and Ni-rich massive sulfide at the base of the intrusion (explored but never mined on a large scale). Because of its unique geology and economically important mineralization, the Stillwater Complex has been the subject of intense scrutiny by both industry and academia since its discovery, and continues to be to this day.

The only other known layered mafic/ultramafic complex in Montana is the Lady of the Lake Complex, located in the central Tobacco Root mountains (Horn and others, 1991; Sarkar and others, 2009). The complex exhibits centimeter-scale layering, is rich in ortho- and clinopyroxene, and contains up to 20% modal olivine near its base (Sarkar and others, 2009). The age of the Lady of the Lake Complex, at 74.9 ± 0.2 Ma (Sarkar and others, 2009), is much younger than Stillwater, and overlaps with that of the Tobacco Root Batholith. The complex is reported to contain locally elevated gold, platinum, and palladium values (John Childs, written commun., 2018) but has never been drilled.

Other Chromite Occurrences

In addition to Stillwater, a few outlying chromite deposits of presumed Archean age exist in Montana. The more significant occurrences are near Red Lodge in Carbon County and near the towns of Sheridan, Pony, and Silver Star in Madison County (Jackson, 1963). At both locations, chromite forms irregular pods and lenses in sill-like and/or faulted bodies of serpentinite. These deposits are examples of "Alpine-type" chromite deposits, and differ from the stratiform chromite layers of the Stillwater Complex. Although they are dwarfed in tonnage by the deposits at Stillwater, the smaller bodies reportedly contain chromite of higher purity and grade. A mine near Silver Star produced several thousand tons of Cr-concentrate in WWII (Jackson, 1963). However, in today's global economy, the Montana deposits cannot compete with large reserves of high-purity chromite from overseas mining operations.

Banded Iron Formations

Large deposits of Precambrian banded iron formation (BIF) exist in southwest Montana (Bayley and James, 1973). For example, the Carter Creek deposit, in the western Ruby Range, contains an estimated 95 million tons of ore grading 28–29% Fe, mainly as magnetite (James, 1990). The smaller Kelly iron deposit, in the northeast Ruby Range, contains an estimated 15 million tons at 33% Fe (James, 1990). Other BIF deposits have been mapped in the Gravelly, southern Highland, and southern Tobacco Root Mountains (James, 1981). According to Immega and Klein (1976), the metamorphic grade of BIFs in the Tobacco Roots is higher than in the southern Ruby Range. James (1990) described BIFs in the Ruby Mountains as belonging to the Christensen Ranch Metasedimentary Suite (CRMS), a sequence of shallow platform sediments now metamorphosed to quartzite, marble, schist, gneiss, and BIF, with intervening, mostly concordant, layers of amphibolite. Although James (1990) assigned a late Archean age to the CRMS, more recent interpretations argue these sediments were laid down on a ~2.0–2.1 Ga passive margin of the North American craton and later metamorphosed during the 1.7–1.8 Ga Big Sky Orogeny (Sims and others, 2004; Condit and others, 2015). With this younger age assignment, the deposits of the Ruby Range would belong to the clan of "Superior-type" BIFs that are found worldwide in shallow marine sediments dating to the early Proterozoic (i.e., 2.5–2.0 Ga). This was a time period when the world's oceans were thought to have been anoxic and rich in dissolved Fe^{2+} at the same time that the Earth's atmosphere was slowly becoming oxygenated through the evolution of photosynthetic microorganisms: BIF formations formed on continental shelves where the Fe-rich ocean water was oxidized to precipitate hematite (e.g., Robb, 2005).

Jardine District

Although the Archean and paleo-Proterozoic rocks of Montana host many lode gold and polymetallic vein deposits, in many cases it is not known whether mineralization occurred in the Precambrian or, more likely, during Cretaceous–Tertiary hydrothermal activity. An exception is the Au-W vein deposits of the Jardine district (Reed, 1950; Smith, 1996). These deposits are hosted in Archean metamorphic rocks and can be grouped into two categories (Seager, 1944): (1) quartz veins with high scheelite and relatively low gold content cutting quartz–biotite schist and quartzite; and (2) replacement bodies rich in arsenopyrite (±pyrrhotite, pyrite) and gold cutting quartz–grunerite schist and meta-turbidites. The origin of the gold and associated tungsten mineralization at Jardine is disputed, with most theories falling into either a syngenetic-exhalative or a metamorphic-hydrothermal model. Evidence for the former includes: (1) textures; (2) mineralization being preferably developed in silicate-facies and sulfide-facies banded iron formation; and (3) trace element profiles consistent with a sea-floor volcanic-hydrothermal system (Foster and Childs, 1993). However, later structural, mineralogical, and fluid inclusion studies (e.g., Smith, 1996) provided evidence for gold remobilization during prograde metamorphism and deformation, in a manner similar to so-called "orogenic" gold deposits. Orogenic gold deposits form over a continuum of pressure-depth-temperature conditions, but most are thought to develop from prograde metamorphic fluids at depths near the brittle–ductile transition in the Earth's crust (Groves and others, 1998).

Most historic production in the Jardine district has come from the Jardine mine, first operated in the 1940s, and more recently reopened in the 1960s–1980s as the Mineral Hill mine. Smith (1997) indicated a total, pre-mining reserve of 510,000 oz Au for Jardine/Mineral Hill. Additional deposits with similar geology are known to occur in the area, and sporadic exploration has continued to the present day. These efforts have been legally and environmentally challenged given the district's close proximity to Yellowstone National Park and the Beartooth Wilderness.

There are interesting similarities between the Jardine deposit and the world-class gold deposits of the Homestake mine, South Dakota. At Homestake, gold occurs along with abundant arsenopyrite and pyrrhotite in the hinges of tight folds, and is stratigraphically restricted to the Homestake Formation, a cummingtonite–grunerite schist of paleo-Proterozoic age (Slaughter, 1968). The Homestake Formation, like the grunerite schist at Jardine, is thought to represent a metamorphosed iron formation (Slaughter, 1968; Smith, 1996, 1997). Rostad (1997) pointed out that the best gold ore in the original Jardine mine was located in the hinges of tight folds in the grunerite schist, a situation that is directly analogous to Homestake.

MESOPROTEROZOIC DEPOSITS OF THE BELT BASIN

The Belt–Purcell Basin of Montana, northern Idaho, and southeastern British Columbia is host to a number of important metal deposits (fig. 1). A useful summary of the metallogeny of the Belt–Purcell Basin can be found in Lydon (2007). By far the biggest past producer is the Sullivan mine, in southern British Columbia, one of the largest lead–zinc–silver deposits in the world. Sullivan is an example of a "sediment-hosted exhalative" or "SEDEX" hydrothermal deposit. SEDEX deposits form in active rift basins near continental margins and accumulate where metalliferous brines vent on the sea floor or replace footwall sediments. Whereas Sullivan is in southern British Columbia, at least two SEDEX-style deposits are known to exist in the Montana part of the Belt Basin, and these are described below. Second in importance to Sullivan are the sediment-hosted "red bed" copper–silver deposits contained in the Revett Formation of northwestern Montana, including the Troy (Spar Lake), Montanore, and Rock Creek deposits, also discussed below.

SEDEX Deposits

Operated by Cominco for over 100 yr, the rich ores of Sullivan were eventually depleted and mining ceased in 2001. Searching for new Sullivan-style deposits, Cominco conducted an aggressive regional exploration program in the Montana portion of the Belt Basin in the 1970s. At least two significant sulfide deposits were defined, the bigger of the two being Black Butte (originally called Sheep Creek), located near White Sulphur Springs. Descriptions of the geology and mineralization at Black Butte include Himes and Petersen (1990), Zieg and others (1993), Graham and others (2012), and White and others (2014). Unlike most SEDEX deposits that are mined primarily for zinc and lead, the Black Butte deposit is rich in copper with important cobalt, nickel, and silver, and relatively minor amounts of Pb-Zn. The mineralization is dominated by chalcopyrite with subordinate tennantite and is contained within several stratiform, massive to semi-massive pyrite lenses in the Newland Formation, a marine black shale with dolomite and debris flow interbeds. Barite is locally abundant, especially in the so-called upper sulfide zone of the Strawberry Main deposit, and the enclosing shales are silicified where copper grades are highest (Graham and others, 2012). The copper-rich zones locally contain disseminated Co-Ni sulfides and sulfarsenides (White and others, 2014).

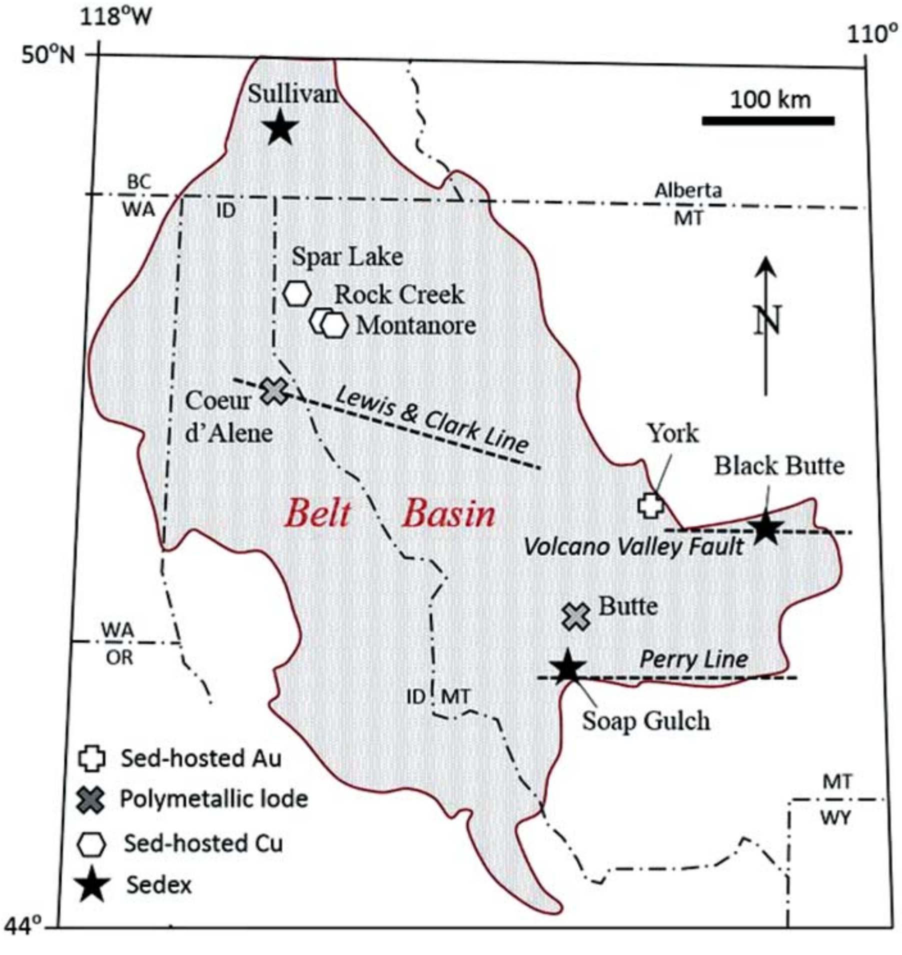


Figure 1. Generalized map of the mid-Proterozoic Belt–Purcell Basin showing the location of mines and prospects discussed in the text (modified from Lyons and others, 2000).

The upper zone of the Johnny Lee deposit at Black Butte has a measured resource of 2.66 Mt grading 2.99% Cu, 0.12% Co, 16.3 g/t Ag, and an indicated resource of 6.52 Mt at 2.77% Cu, 0.13% Co, and 15.5 g/t Ag (White and others, 2014). Additional mineralized zones exist on the property and are currently being evaluated. Hematitic gossan formed by weathering of a massive pyrite lens in the Newland Formation has been mined at a small scale for iron ore at a location roughly 4 km west of Black Butte (Reed, 1949).

A second SEDEX-style sulfide deposit explored by Cominco is located up Soap Gulch in the western Highland Mountains. The deposit, also marked by an extensive gossan at the surface, is hosted by dark argillite and dolomite of the LaHood Formation (McDonald and others, 2012), previously mapped as the Newland Formation by O'Neill and others (1996). Although no papers could be found on the geology of the Soap Gulch deposit, the prospect is said by local geologists to be primarily enriched in zinc. SEDEX-style massive sulfide mineralization in lower Belt sediments has also been reported from Wickiup Creek (Thorson, 1984), a few kilometers to the east from Soap Gulch, and at the "Calico Prospect" in Cardwell, a few kilometers east of the Golden Sunlight mine (Bruce Cox, oral commun., 2017). A prominent gossan on the summit of Mount Evans, in the Anaconda Range, may be the metamorphosed remnant of a SEDEX-style sulfide deposit in lower Belt metasediments (Eastman and others, 2017a).

"Red Bed" Copper–Silver Deposits

Sediment-hosted copper mineralization ("red-bed copper") can be found in many of the sedimentary formations of the Belt Basin (Harrison, 1972). Earhart and others (1981) reported as many as 16 sequences of copper enrichment in the Spokane Formation, each hosted by green interbeds within what is predominantly a red siltite/argillite. However, all of the economically important sediment-hosted deposits of this type in Montana are found in white or gray quartzites of the Revett Formation of the Ravalli Group (Harrison, 1972). These include the recently closed Spar Lake mine near the town of Troy, and the Rock Creek/Montanore deposit, currently in the permitting stage. Total metal endowment (production + reserves) at Spar Lake is estimated at 550 million lbs Cu and 65 million oz Ag (Boleneus and others, 2005). The same source cites total reserves of 5 billion lbs Cu and 679 million oz Ag at the Rock Creek/Montanore deposit, making it one of the largest silver deposits in the U.S. (surpassed only by Couer d'Alene, Idaho, and Butte, Montana) and the 20th largest stratabound copper deposit in the world (Boleneus and others, 2005). Although initially owned by two separate mining companies, the Rock Creek and Montanore deposits are part of the same contiguous, shallow-dipping ore body that can be traced from one side of the Cabinet Mountains to the other.

As a group, most sediment-hosted copper deposits form near a redox interface between oxidized (red) and reduced (grayish, green, or black) sedimentary layers (e.g., Hitzman and others, 2010). In the case of the Revett deposits, overprinting low-grade metamorphism has muted the color differences that may have existed in the Precambrian, obscuring redox relationships (Hayes and Einaudi, 1986). Currently, the oxidized horizons in the Revett have a lavender-gray hue and contain disseminated specular hematite while the reduced horizons are gray-white or gray-green with sparse pyrite, calcite, and chlorite (Hayes and Einaudi, 1986; Boleneus and others, 2005). Ore minerals, mainly chalcocite and bornite, are found exclusively in the reduced horizons, and are concentrated along bedding planes and fractures in coarse-grained sandstone. Disseminated pyrite is paragenetically early and is mostly replaced by Cu-sulfides in the ore zones. Even in the ore-bearing strata, sulfide minerals rarely exceed a few percent of the rock. This is a contrast to the SEDEX-style, Cu-rich ore bodies at Black Butte (discussed above), which are contained in zones of nearly massive pyrite.

Lange and Sherry (1983) and Hayes and Einaudi (1986) presented similar models in which oxidized, metalliferous brines sourced from deeper in the Belt Basin moved upwards along steeply dipping faults and then migrated laterally through the permeable quartz sandstones of the Revett, depositing Cu-sulfides and other ore minerals at the transition from oxidized to reducing conditions. More recently, Hayes and others (2012) have suggested that the reductant that triggered copper sulfide deposition was a reservoir of sour (H_2S-rich) natural gas that had migrated into the Revett sandstone during early diagenesis of the Belt Basin. The only remaining evidence of this ancient natural gas field is the presence of methane and other hydrocarbons trapped in fluid inclusions in gangue minerals within the deposits.

Stratabound Gold Deposits in the Greyson Formation

In the vicinity of the historic York placer district, on the west flank of the Big Belt Mountains, the middle member of the Greyson Formation of the lower Belt sequence contains a number of gold deposits associated with stratabound, erosion-resistant “reefs.” The reefs contain abundant epigenetic K-feldspar with sparse pyrite and Fe-carbonates along bedding planes and in cross-cutting quartz–carbonate veins (Foster and Childs, 1993; Tysdal and others, 1996; Thorson and others, 1999; Whipple and Morrison, 1999; Christiansen and others, 2002). Although most reefs are parallel to bedding, they locally cross-cut the stratigraphy at a low angle. East of Trout Creek, as many as 10 or more individual reefs up to 30 m thick have been recognized, the largest having strike lengths of >1 km. Although the overall gold concentrations are low, the large and laterally persistent nature of the reefs led Christiansen and others (2002) to report a resource of 12.5 M oz of gold at grades >0.3 g/ton. The origin of the stratabound gold mineralization is debated. Early workers (Thorson and others, 1999) felt that the reefs formed in the Precambrian by either a syngenetic-exhalative or a diagenetic-replacement model. However, Christiansen and others (2002) obtained a K/Ar date of 89 ± 3.2 Ma for hydrothermal K-feldspar, and reported that unpublished U/Pb and Rb/Sr data also support a Cretaceous age for the reefs.

PHANEROZOIC METAL DEPOSITS

From a metallic ore deposit point of view, the late Proterozoic and Paleozoic Eras, as well most of the Mesozoic Era, were a bust in Montana. During this time, most of what is now the northern Rockies was a vast, nearly flat continental shelf, receiving mostly marine sediments during extended episodes of sea-level rise (e.g., the Cambrian), and erosion of those sediments during times of sea-level decline (e.g., during the Ordovician–Silurian). The only rocks of economic importance that formed between 1,000 and 100 million years ago were vast deposits of limestone, building stone, hydrocarbon source rocks, coal, and industrial minerals. The latter include the huge reserves of phosphorite in the Permian Phosphoria Formation of east Idaho, west Wyoming, and southwest Montana. This extended period of tectonic inactivity ended when the effect of the distant collision of the Farallon Plate with western North America reached Montana in mid-Cretaceous time. The ensuing Sevier and Laramide orogenies brought deformation, metamorphism, and plutonic activity to much of western and central Montana, along with a rich and diverse inventory of hydrothermal mineral deposits.

The following sections are organized more by ore deposit type than by age, so that deposits that share geologic characteristics can be discussed together.

Porphyry Cu-Mo Deposits

Porphyry Cu-Mo deposits are some of the largest metallic mineral deposits in the modern mining industry. Some porphyry deposits are also rich in precious metals, including gold (e.g., Bingham Canyon, Utah) and silver (Butte). Although many subtypes of porphyry deposits have been recognized in the literature, the majority can be classified as either: (1) Cu-dominant with byproduct Mo ± Au, (2) Mo-dominant (also known as “Climax-type”) with no significant Cu; and (3) Sn-(W) dominant. Mineralized intrusions that form porphyry-style deposits may release metal-rich fluids that migrate into the country rock to form other types of hydrothermal ores, such as skarns, polymetallic veins and lodes, carbonate replacement deposits, and epithermal deposits.

The Butte porphyry/lode deposit, mined from the 1870s to the present day, is one of the top 10 copper mining districts in the world, and has produced enormous quantities of other metals, including silver, zinc, lead, molybdenum, gold, and manganese. The history of mining of the Butte ore bodies is interwoven with the history of the State of Montana, and many books have been written on this subject. Butte is unusual compared to most porphyry deposits in that a majority of the valuable metals (with the exception of molybdenum) were mined from lodes that crosscut the earlier porphyry-style mineralization. Butte also has a more diverse mineral and metal assemblage than the average porphyry deposit, which is one reason it has been the subject of intense study by economic geologists for over a century. A review of the geology and geochemical evolution of the Butte deposit is given in a separate chapter of this volume (Reed and Dilles, 2020). More recently, Butte has become synonymous with the word “Superfund.” The legacy of 150 years of mining, milling, and smelting the great ores of Butte have left an enormous environmental burden. A review of some of these issues, focusing on the Berkeley Pit lake, is given by Gammons and Duaime (2020).

Exploration drilling by various companies has documented that a number of porphyry Cu-Mo and porphyry Mo deposits exist in Montana outside of the Butte district. The largest such deposit for which grade-tonnage data are available is the Heddleston deposit (Miller and others, 1973), located near the headwaters of the Blackfoot River. According to Singer and others (2005), Heddleston contains a total resource of 302 million tons at 0.36% Cu, 0.005% Mo, 0.053 g/ton Au, and 5.2 g/ton Ag. McClave (1998) reported a mineable reserve of 93 million tons averaging 0.48% Cu. The geology of Heddleston consists of Eocene quartz monzonite stocks and dikes cutting argillite and siltite of the Belt-aged Spokane Formation and a late Proterozoic diorite sill. Porphyry-style mineralization is found in the quartz monzonite, in the Spokane Formation, and in the sill. A date (K/Ar) for hydrothermal sericite of 44.5 Ma (McClave, 1998) makes Heddleston roughly 20 m.y. younger than the Butte deposit. A number of late, polymetallic veins surround the central quartz monzonite stock, including the historic Mike Horse mine, notorious for its 1975 tailings dam failure that polluted the upper Blackfoot River (Spence, 1997). Unlike the Main Stage veins of the Butte district (Reed and Dilles, 2020), the late veins at Heddleston were relatively impoverished in copper. A recent study (Schubert and Gammons, 2018) has shown that the S-isotopic compositions of pyrite in porphyry-style and lode-style mineralization in the Heddleston district are similar to each other, and overlap with the $\delta^{34}S$ of stratabound Cu-Ag deposits in the surrounding Belt sediments (Byer, 1987). The isotopic values also overlap with the $\delta^{34}S$ of pyrite from the Butte deposit (Lange and Cheney, 1971; Field and others, 2005). Thus, although separated by at least 20 m.y., the two porphyry systems may have inherited their sulfur, and possibly much of their metal endowment, from a similar source region.

Other porphyry Cu (± Au, Mo) deposits of Montana are shown in figure 2. Most of these have extensive areas of porphyry-style alteration but no publicly documented grade/tonnage information. Some of the deposits (e.g., Emigrant Gulch, Golconda, Lowland Creek, Radersberg, Turnley Ridge) need more exploration drilling to assess their economic importance. All of the porphyry Cu-Mo deposits of the Boulder Batholith are inferred to be late Cretaceous or early Tertiary (Paleocene), although Butte is the only such deposit with reliable dates. Porphyry-style, pre-Main Stage mineralization at Butte is dated at 64.5 Ma (Lund and others, 2002) and is roughly 10 million years younger than the main host rock of the district, the Butte Granite. It is not known if other porphyry Cu-Mo deposits in the batholith are of similar age. Porphyry Cu deposits outside of the batholith to the north and west (Heddleston, Copper Cliff) and to the southeast (Emigrant Gulch, New World) are Eocene. At least two of the Eocene deposits (Copper Cliff and New World) carry significant gold along with copper.

Porphyry Mo Deposits

A number of "Climax-type" porphyry-Mo deposits exist in Montana, although none have been mined. Based on a review by Worthington (2007), the largest known deposits are Cannivan Gulch in the Pioneer Mountains (300 Mt at 0.06% Mo with some higher grade zones) and Big Ben in the Little Belts (376 Mt at 0.098% Mo). Armstrong and others (1978) obtained a K/Ar date of 59 ± 2 Ma for hydrothermal muscovite at Cannivan Gulch, indicating an early Tertiary (Paleocene) age. Rostad and others (1978) reported ages of 49.5 and 48 Ma for the Big Ben and Bald Butte porphyry-Mo deposits, respectively. These deposits are situated at the NE end of the "White Cloud–Cannivan porphyry Mo belt" of Armstrong and others (1978), also known as the "Idaho–Montana porphyry belt" or "transverse porphyry belt." This belt of deposits is roughly parallel to the northeast–southwest-trending Colorado mineral belt, home to the world-class Climax and Henderson porphyry-Mo deposits. Rostad and others (1978) pointed out that the Idaho–Montana belt exhibits a close spatial and genetic association between porphyry-style Cu-Mo deposits, Au-Ag-Cu-W skarn deposits, and epithermal-style Au-Ag mineralization. Spry and others (1996) describe the main breccia pipe at the Golden Sunlight gold mine as being underlain by a Mo-rich porphyry deposit, although details have not been published. It is interesting to note that all of the known porphyry deposits in the Pioneer and Flint Creek mountains are Mo-rich, whereas most of the deposits in the Boulder Batholith are Cu-rich with minor Mo.

Skarn Deposits

Most skarn deposits form at the contact of a carbonate rock with a mineralized, water-rich igneous intrusion. Skarns that develop in limestone or in dolomite are referred to as "calcic skarns" or "magnesian skarns," respectively (Meinert and others, 2005). Most of the magnesian skarns in Montana are hosted by the Cambrian Pilgrim/Hasmark or the Devonian Jefferson

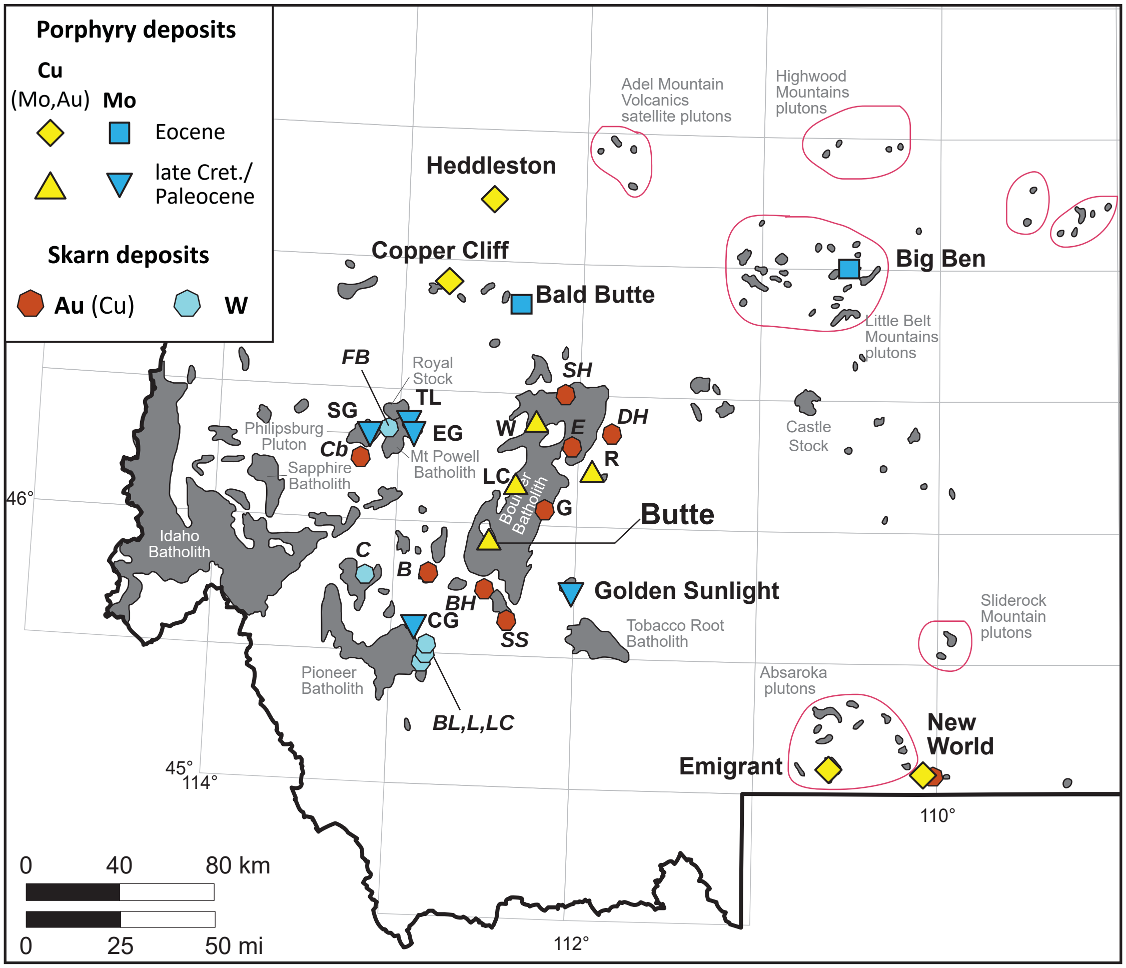


Figure 2. Location of porphyry and skarn deposits of western Montana. Abbreviations and references: B, Beal (Wilkie, 1996); Bald Butte (Tysdal and others, 1996); Big Ben (Olmore, 1991); BH, Butte Highlands (Ettlinger and others, 1996); BL, Brownes Lake (Pattee, 1960); C, Calvert (Messenger, 2016); Cb, Cable (Cox and Bogert, 2017); CG, Cannivan Gulch (Darling, 1994); Copper Cliff (Fairbanks, 2009); DH, Diamond Hill (Pearson and others, 1992); E, Elkhorn/Golden Dream (Steefel, 1982); EG, East Goat (Ericksen and others, 1981); Emigrant (Worthington, 2007); G, Golconda (Greenwood and others, 1990); Golden Sunlight (Spry and others 1996); H, Heddleston (McClave 1998); LC, Lowland Creek (Fess Foster, oral commun.); LC, Lost Creek (Collins, 1977); New World (Johnson and Meinert, 1994); R, Radersberg (Tysdal and others, 1996); SG, Stewart Gulch (Antonioli, 2009); TL, Tolean Lake (Ericksen and others, 1981); W, Wickes/Beavertown (Elliott and others, 1986; Tysdal and others, 1996).

Formations, whereas the calcic skarns are mainly in the Cambrian Meagher Formation or the Mississippian Madison Group. Both types have similar skarn minerals, usually including garnet (grossular, andradite), clinopyroxene (diopside, hedenbergite, augite), epidote, quartz, and magnetite/hematite. Mg-skarns may also contain forsterite and serpentine (alteration product of forsterite). Retrograde alteration forms lower temperature minerals such as calcite, tremolite/actinolite, and micas (biotite, phlogopite, chlorite, muscovite). Selected photographs of skarns from Montana are shown in figure 3.

In terms of metal endowment, the skarns of Montana fall into two categories: (1) Au (± Ag, Cu)-skarns and (2) W-skarns. Locations of individual deposits mentioned in the text are shown in figure 2, and table 1 summarizes some geological and grade/tonnage information. All skarns developed in the Boulder Batholith are rich in gold, whereas most skarns in the Pioneer and Flint Creek mountain ranges are rich in tungsten. Some of the bigger gold skarns in Montana include the Beal Mountain, Butte Highlands, Silver Star (Madison Gold), Elkhorn (Golden Dream), and Diamond Hill deposits, all of which occur around the fringe of the Boulder Batholith, and the New World skarn near Cooke City. The New World deposit is unlikely to be mined in the foreseeable future given a 1996 Federal decision to terminate exploration and development in the district because of its proximity to Yellowstone National Park. The skarn at New World is closely associated with porphyry-style Cu-Au and carbonate replacement Pb-Zn-Ag mineralization contemporary with intrusion of Eocene stocks into Paleozoic metasediments (Johnson and Meinert, 1994). A similar

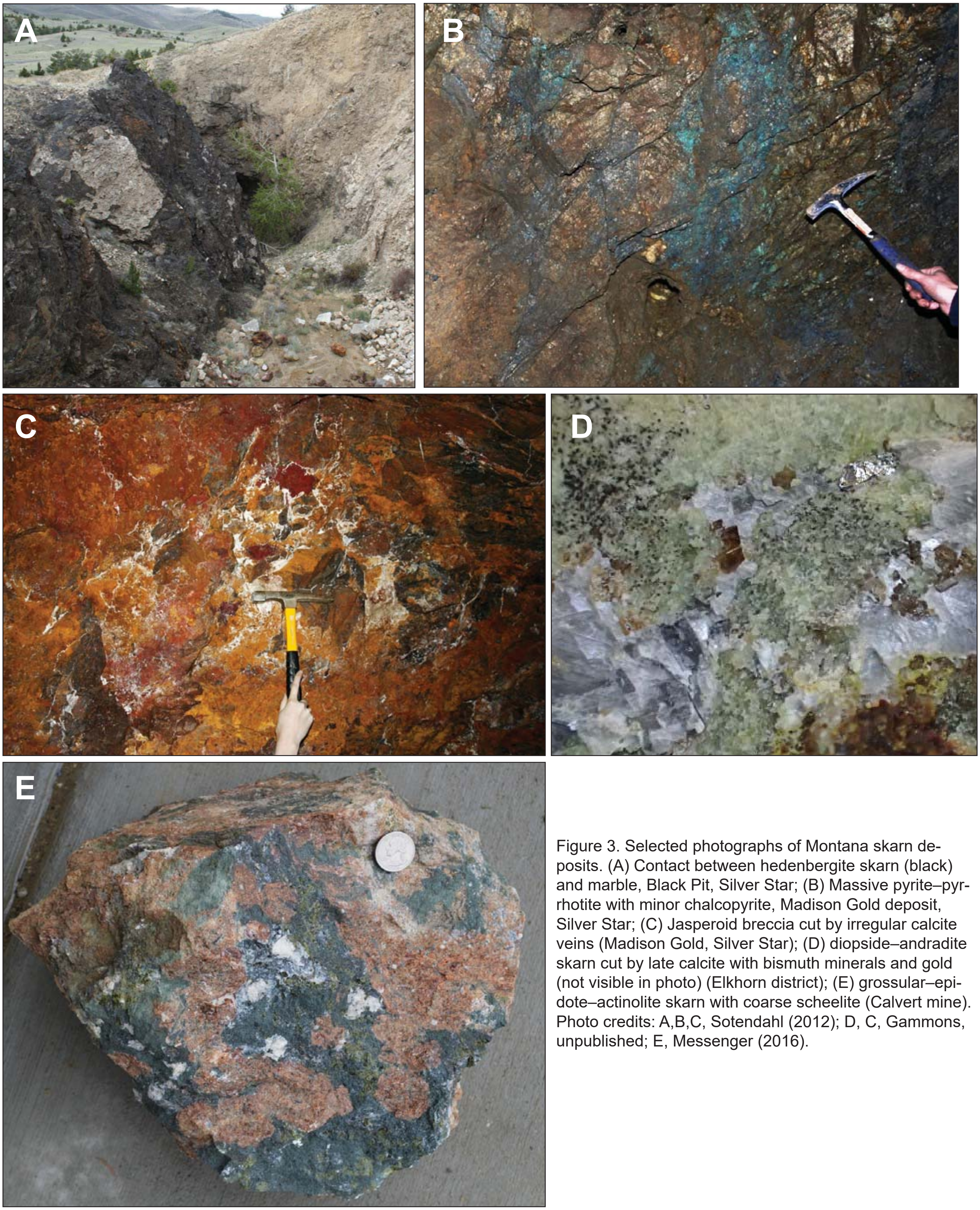


Figure 3. Selected photographs of Montana skarn deposits. (A) Contact between hedenbergite skarn (black) and marble, Black Pit, Silver Star; (B) Massive pyrite–pyrrhotite with minor chalcopyrite, Madison Gold deposit, Silver Star; (C) Jasperoid breccia cut by irregular calcite veins (Madison Gold, Silver Star); (D) diopside–andradite skarn cut by late calcite with bismuth minerals and gold (not visible in photo) (Elkhorn district); (E) grossular–epidote–actinolite skarn with coarse scheelite (Calvert mine). Photo credits: A,B,C, Sotendahl (2012); D, C, Gammons, unpublished; E, Messenger (2016).

Table 1. Summary data for skarn deposits of Montana.

Deposit/Mine	Ore Minerals	Tonnage/Grade	Host Rock	Age of Associated Intrusion	Refs
Gold (Copper) Skarns: Magnesian Subtype					
New World	Au-Cu	12.0 Mt, 0.22 oz/t Au, 0.87 oz/t Ag, 0.75% Cu	Meagher Fm.	Eocene (Homestake Intrusive Complex)	Johnson & Meinert, 1994; Johnson & Thompson, 2006
Highlands	Au,po,cp,mt (py)		Meagher, Wolsey Fms.	Late Cretaceous Burton Park Pluton of Boulder Bath.)	Ettlinger and others, 1996
Cable (Georgetown)	Au,py,po,cp	0.165M oz Au	Hasmark Fm.	Late Cretaceous ± Tertiary overprint Cable granodiorite stock	Elliott and others, 1986
Elkhorn (Golden Dream)	Au-Cu??	1.1Mt, 0.23 oz/t Au, 0.43% Cu	Meagher Fm.	Late Cretaceous	Weed, 1902; Klepper and others, 1957; Everson and others, 1992
Gold (Copper) Skarns: Calcic Subtype					
Silver Star (Broadway, Madison Gold)	Py,po,cp,cc,el,g Bi-Ag tellurides,		Madison Group	Late Cretaceous (Rader Creek granodiorite of Boulder Bath.)	Foote, 1986; Sotendahl, 2012; Gammons and others, 2010
Spring Hill	Au, asp, py, po	38,000 oz Au	Madison	Late Cretaceous	Jones, 1934
Indian Queen	Au-Cu??	minor	Madison	Late Cretaceous	Geach, 1972
Gold (Copper) Skarns: Other					
Beal	Py,po,as,cp,g	14.8Mt, 1.49g/t Au	Blackleaf Fm.	Late Cretaceous German Gulch pluton of Boulder Bath.)	Hastings & Harrold, 1987; Wilkie,1996
Diamond Hill	Py,po,cp,g,gn,sp, Bi-tellurides	1.1Mt, 0.271oz/t Au	Elkhorn Mtn. volcanics	Late Cretaceous? (Diamond Hill stock)	Pearson and others, 1992
Tungsten Skarns					
Brownes Lake	sch (Mo-rich)	0.62Mt, 0.35% WO3	Amsden Fm.	Pioneer Batholith	Pattee, 1960
Lentung	sch	3.3Mt, 0.48% WO3	Amsden Fm.	Pioneer Batholith	Deboer, 1991
Lost Creek	sch	0.02Mt, 0.18% WO3	Amsden Fm.	Pioneer Batholith	Pattee, 1960, Collins, 1977
Finlay Basin	sch	0.85Mt, 0.68% WO3	Madison	Royal Stock of Philipsburg Batholith	Elliott and others, 1986
Calvert	sch (minor py,po,cp)	0.22Mt, ~1% WO3	Amsden?	Late Cretaceous Foolhen Tonalite	Messenger, 2016; Messenger and Gammons, 2017

Note. Ore Minerals: as, arsenopyrite; cc, chalcocite; cp, chalcopyrite; el, electrum; Au, gold; g, garnet; po, pyrrhotite; py, pyrite; sch, scheelite, gn, galena; sp, sphalerite.

association exists at Elkhorn, where several gold-rich skarns and breccia pipes are found near the contact with the Late Cretaceous Turnley Ridge porphyry intrusion, a host to low-grade Cu-Mo mineralization (Steefel and Atkinson, 1984).

Most gold skarns in Montana share a similar ore mineralogy, being rich in pyrrhotite and magnetite, with lesser amounts of chalcopyrite, arsenopyrite, and pyrite. Bi-sulfides or Bi-Ag-tellurides are accessory minerals. Gold may occur as electrum or as nearly pure gold, the latter being more common in retrograde skarn or sulfide-bearing skarns that have later been oxidized (Gammons and others, 2010). Because of the relative immobility of gold in the weathering environment compared to silver and base metals, hematitic gossans or jasperoids developed in the oxidized zone of many skarns carry good Au grades, with the additional bonus of being easier to mill and extract the gold. Typical grades of Au in the Montana deposits are 0.1–0.3 opt, and Au mineralization is spotty, leading to challenges with grade control and mine design. The largest gold producer to date, Beal Mountain (German Gulch), is hosted by Cretaceous clastic sediments of the Blackleaf Formation. Nonetheless, it is considered a skarn based on its gangue mineralogy (pyroxenes, garnets, vesuvianite) and proximity to the German Gulch stock. Another significant gold producer, the Diamond Hill mine, is developed in andesite of the Elkhorn Mountains Volcanics. Like Beal Mountain, the Diamond Hill deposit has typical skarn mineralogy despite being hosted by a non-carbonate lithology.

Tungsten skarns of Montana contain scheelite ($CaWO_4$) as the only metallic mineral of economic importance, and most have low concentrations of sulfide minerals such as pyrrhotite, pyrite, chalcopyrite, and molybdenite (Walker, 1960, 1963). Typical grades for the Montana deposits range from about 0.1 to 1.0 wt% WO_3. Two of the larger deposits are Lentung in the east Pioneer Mountains, developed in the Amsden Formation, and Finlay Basin in the Flint Creek Mountains, which is hosted in the Madison Limestone. The Lentung deposit is an underground resource between similar skarn mineralization at Brownes Lake, to the north, and Lost Creek, to the south. The published resource is 3.3 Mt at 0.48% WO_3 (Deboer, 1991), although the deposit has not been completely drilled out and is open along strike. There is also a possible market for byproduct garnet from the scheelite skarns (E.E. Nelson, oral commun., February 2018). Messenger (2016) and Messenger and Gammons (2017) completed a mineralogy, fluid inclusion, and stable isotope study of the Calvert scheelite skarn in the northern Pioneer Mountains, one of the smaller but higher-grade W-skarns in Montana.

Polymetallic Vein and Carbonate Replacement Deposits

Polymetallic (Ag-Pb-Zn±Au±Cu) vein deposits constitute the majority of historic hard-rock mines in Montana. Most polymetallic veins have an abundance of pyrite, sphalerite, and galena, sometimes with chalcopyrite, arsenopyrite, tetrahedrite, and Pb-Sb-As-Ag sulfosalt minerals, in a quartz or quartz–carbonate gangue. Black tourmaline (schorl) is abundant in some veins, especially those that cut the Boulder Batholith in the Wickes and Basin districts (Cox, 2015). Gold may or may not be present in economic quantities. If so, it is often residing as electrum (Au-Ag alloy) or tiny inclusions in pyrite or arsenopyrite. The veins (or lodes, the term for a vein exceeding 3 ft in width) are often continuous along strike and dip for hundreds to thousands of feet, and may have any orientation, although steep dips are more common. Veins may terminate or bifurcate, and many mines in Montana followed multiple veins. Some veins are strongly sheared. Host rocks can be igneous, sedimentary, or metamorphic, although veins cutting carbonate rocks are less common, owing to the tendency of hydrothermal fluids to replace limestone rather than to break it.

Carbonate replacement deposits are so-named because the ore-forming fluids dissolved the carbonate matrix and deposited sulfide minerals in its place. Such deposits differ from skarns (preceding section) in that they lack evidence of high-temperature metasomatism of the wall rock (e.g., presence of prograde skarn minerals, such as garnets, pyroxenes). The carbonate replacement deposits in Montana are similar in mineralogy and tenor to the fissure veins, but have a more complex geometry with ore distributed along bedding planes, in the hinges of folds, along faults, and sometimes as sinuous, irregular deposits (i.e., chimneys or mantos; see fig. 4). The important mines of the Hecla and Elkhorn districts as well as many of the mines in the Philipsburg district fall into this category.

The distinction made in this paper between polymetallic vein/replacement deposits and epithermal deposits (next section) is based on the inferred conditions of depth and sources of ore fluids. Whereas

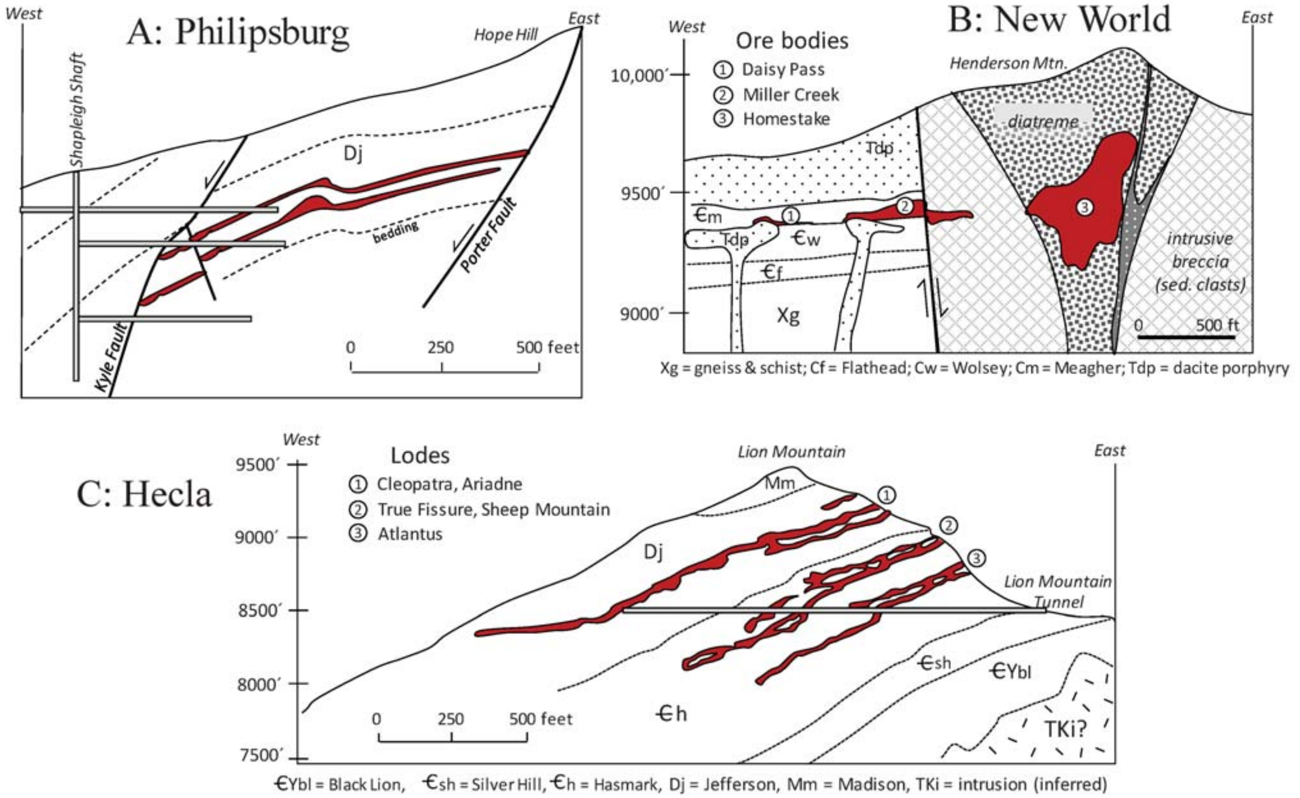


Figure 4. Simplified cross sections through three polymetallic, carbonate-replacement ore bodies in Montana. (A) Philipsburg (Hope Hill area, from Emmons and Calkins, 1913); (B) New World (from Johnson and Thompson, 2006); (C) Hecla (from Karlstrom, 1948). Ore bodies are shown in red.

epithermal deposits form in the top 1–2 km of the Earth's crust with major involvement of heated meteoric waters, the polymetallic deposits discussed in this section are thought to have formed at greater depths from primarily magmatic fluids. However, very few of the polymetallic lode deposits of Montana have been examined by modern methods of ore deposit study. Zimmerman (2016) and Korzeb and others (2018) conducted detailed fluid inclusion and stable isotope studies of the Emery (Zosell) district, east of Deer Lodge, and concluded that the ore fluids were dominantly magmatic and that the veins formed at depths exceeding 4 km. The Emery veins cut basaltic andesite of the Elkhorn Mountains Volcanics (EMV), and have a classic polymetallic mineral suite of pyrite, arsenopyrite, galena, sphalerite with minor chalcopyrite, Ag-rich tetrahedrite, electrum, and boulangerite (a Pb-Sb sulfosalt) in a quartz–carbonate gangue. Korzeb and others (2018) obtained a ^{40}Ar/^{39}Ar date of 77.93 ± 0.20 Ma on sericite from a previously unmapped altered granodiorite stock along the extension of the Emery vein system. This date overlaps with U-Pb ages obtained on zircons from the EMV (Korzeb and others, 2018). Similarly, Lund and others (2002) obtained ^{40}Ar/^{39}Ar dates ranging from 73.9 to 77.0 Ma for hydrothermal sericite in altered wall rock at the Eva May and Hope-Bullion mines in the Basin mining district.

Although grades of the polymetallic lode deposits of Montana were often high, tonnages were typically low, with most historic mines producing fewer than 1,000 tons. A large mine might have been >10,000 tons, and a very large mine (by pre-1960s standards) might have processed a million tons over its lifetime, which may have stretched from the late 19th to the mid-20th century. Table 2 lists a few of the larger polymetallic vein and carbonate replacement deposits of Montana. This list excludes Butte, which would be off the scale of comparison. A major stumbling block in compiling this type of list is the lack of accurate production records prior to 1900. For example, the Alta mine, one of the larger Pb-Ag deposits in Montana (excluding Butte), is said to have produced more wealth in the 25 years prior to 1902, most of it as silver, than in all subsequent years, but detailed production figures are nonexistent. Another consideration when scanning the data in table 2 is that, prior to about 1920, zinc was rarely recovered from the polymetallic deposits. This explains why some early mining camps (e.g., Hecla, Alta, Neihart) have anomalously low zinc production figures despite an abundance of sphalerite in the ores.

Table 2. Summary data for selected polymetallic mining districts of Montana (>100,000 tons of ore), excluding Butte.

Mine/ Mining District	County/ Mining District		Years of Recorded Production	Gold (1,000 oz)	Silver (1,000 oz)	Copper (tons)	Lead (tons)	Zinc (tons)	Refs.
Comet Mine / Basin District	Jefferson	Fissure veins and shears cut Butte Granite, andesite. Abundant schorl.	1904–1950	41.7	3,153	1,117	14,111	11,918	Becraft and others, 1963; Tysdal and others, 1996
Alta Mine/ Wickes District	Jefferson	Fissure veins and shears cut andesite near contact with Butte Granite. Abundant schorl.	1902–1957	8.2	1,165	273	4,067	617	Becraft and others, 1963; Tysdal and others, 1996
Argenta District	Beaverhead		1902–1965	72.2	562	302	9,094	1,000	Winchell, 1914; Shenon, 1931; Loen and Pearson, 1984
Silver Dyke Mine / Neihart District	Cascade	Fissure veins and shears cut quartz porphyry and Archean gneiss.	1921–1948	1.7	3,177	3,727	8,183	4.2	Schafer, 1935; Robertson & Roby, 1951
Elkhorn District	Powell	Carbonate replacements in Pilgrim and Jefferson Fms.	1902–1957	61.3	6,152	513	6,202	1,602	Tysdal and others, 1996; Steefel, 1982
Hecla District	Beaverhead	Carbonate replacements in Hasmark and Jefferson Fms.	1873–1965	18.2	13,384	4,135	56,000	1,915	Karlstrom, 1948; Eastman and others, 2017
Philipsburg District		Veins and replacements in igneous rock and Proterozoic and Paleozoic sediments	1904–1962	83	24,000	2,000	11,500	40,000	Emmons and Calkins, 1913; Prinz, 1967
New World District		Porphyry Cu-Au, skarns, and carbonate replacements in Cambrian sediments.	Mostly unmined						Johnson & Meinert, 1994; Johnson & Thompson, 2006
Keating Mine Radersburg District		Fissure veins cut Elkhorn Mtn volcanics.	1864–1956	158	43.6	1,064	n.a.	n.a.	Klepper and others, 1971; Tysdal and others, 1996

The Philipsburg district, in the southern Flint Creek Mountains, is unique in that it contains important deposits of both fissure vein and carbonate replacement types in close proximity. It also has a more complex metal endowment, including tungsten (as huebnerite) and manganese (as Mn-oxides, rhodochrosite, and rhodonite). Emmons and Calkins (1913) noted the similarity in mineralogy and metal ratios in the granite-hosted and sediment-hosted lodes, and concluded that both sets of veins had a common origin, i.e., fluids that were expelled from the granitic batholiths of the Flint Creek Mountains. These observations apply at a district scale as well. Thus, the grades and proportions of ore minerals in the carbonate replacement ores at Hecla and Elkhorn are similar to those of the fissure veins and shear zones of the Basin, Wickes, Neihart, and Argenta districts. In virtually every case, there is compelling geologic evidence to link the polymetallic mineralization to nearby porphyritic intrusions. Thus, the Ag-Pb-Zn carbonate replacement ores at Elkhorn are thought to be the distal expression of ore fluids emanating from the nearby Turnley Ridge porphyry (Steefel and Atkinson, 1984), and a buried porphyry is suspected beneath the Hecla structural dome (Gignoux, 2000). Eastman and others (2017b) used fluid inclusion and stable isotope methods to conclude that the carbonate replacement deposits at Hecla formed from magmatic fluids at temperatures exceeding 300˚C, not from basinal brines of the Mississippi Valley Type association as previously speculated by McClernan (1983). The shear and fissure veins of Basin and Wickes, which cut granite of the Boulder Batholith and overlying Elkhorn Mountain Volcanics, are distributed around the periphery of an unmined porphyry Cu-Mo deposit (Beavertown deposit, Tysdal and others, 1996). The rich Ag-Pb veins of Neihart, hosted by Archean metamorphic rocks, are close to the Big Ben porphyry-Mo deposit in the Little Belt Mountains. A large but low-grade porphyry-Cu system is associated with the Ag-Pb veins of the Argenta district, in the southern Pioneer Mountains (Ted Antonioli, oral commun.). A genetic link is well established between the incredibly rich polymetallic Main Stage veins and lodes of Butte and earlier porphyry-style Cu-Mo mineralization (see Reed and Dilles, 2020), as well as the high-grade carbonate replacement deposits at New World and nearby skarn and porphyry-style ore (Johnson and Meinert, 1994; Johnson and Thompson, 2006).

A distinct cluster of polymetallic vein deposits exists in far western Montana (Mineral County) along structures related to the Lewis and Clark Line. These Ag-Pb-Zn±Au-bearing veins have long been considered an eastern extension of the famous Coeur d’Alene mining district of northern Idaho (e.g., Moore, 1910). The “east Coeur d’Alene veins” are hosted in highly deformed sedimentary rocks of the Belt Supergroup and occur on regional-scale faults that can be traced directly into the principal mines in Silver Valley, Idaho (Lonn and McFaddan, 1999). The most notable examples in Montana are the Iron Mountain mine north of Superior (Campbell, 1960) and the Tarbox and Black Traveler mines north of Saltese, both of which are located on a strand of the Osburn fault zone. Assuming that these deposits are an extension of the Couer d’Alene district, the origin of the Montana deposits is closely tied to the origin of the Silver Valley deposits, which itself is a topic of long-standing controversy outside the scope of this volume.

Epithermal Gold–Silver Deposits

Montana has a number of precious metal deposits that are inferred to be epithermal in origin (fig. 5, table 3), that is, having formed in the top 1–2 km of the Earth’s crust. In the economic geology literature, it has become customary to subdivide epithermal deposits into high sulfidation (HS) and low sulfidation (LS) subtypes (e.g., Simmons and others, 2005). HS epithermal deposits contain prominent vertical zones of vuggy quartz and advanced argillic alteration (quartz–alunite–clay) that often grade with depth to genetically related porphyry Cu±Mo±Au deposits. In contrast, LS deposits display a more pH-neutral alteration style (adularia–sericite with carbonate gangue minerals present), usually with no direct association with porphyry deposits. However, some of the biggest epithermal deposits of Montana are difficult to classify using this scheme. Also, whereas most epithermal deposits are hosted by volcanic rocks, many of the deposits in Montana are not. For example, at Zortman–Landusky, auriferous quartz–pyrite veins cut an altered syenite intrusion and adjacent metamorphosed country rock. At Drumlummon, quartz–carbonate veins and lodes cut Belt-aged metasediments near the contact of the Marysville Stock. At Kendall and the deposits of the Judith Mountains, base and precious metals occur as veins and replacements in Paleozoic carbonate rocks near contacts with Tertiary intrusions.

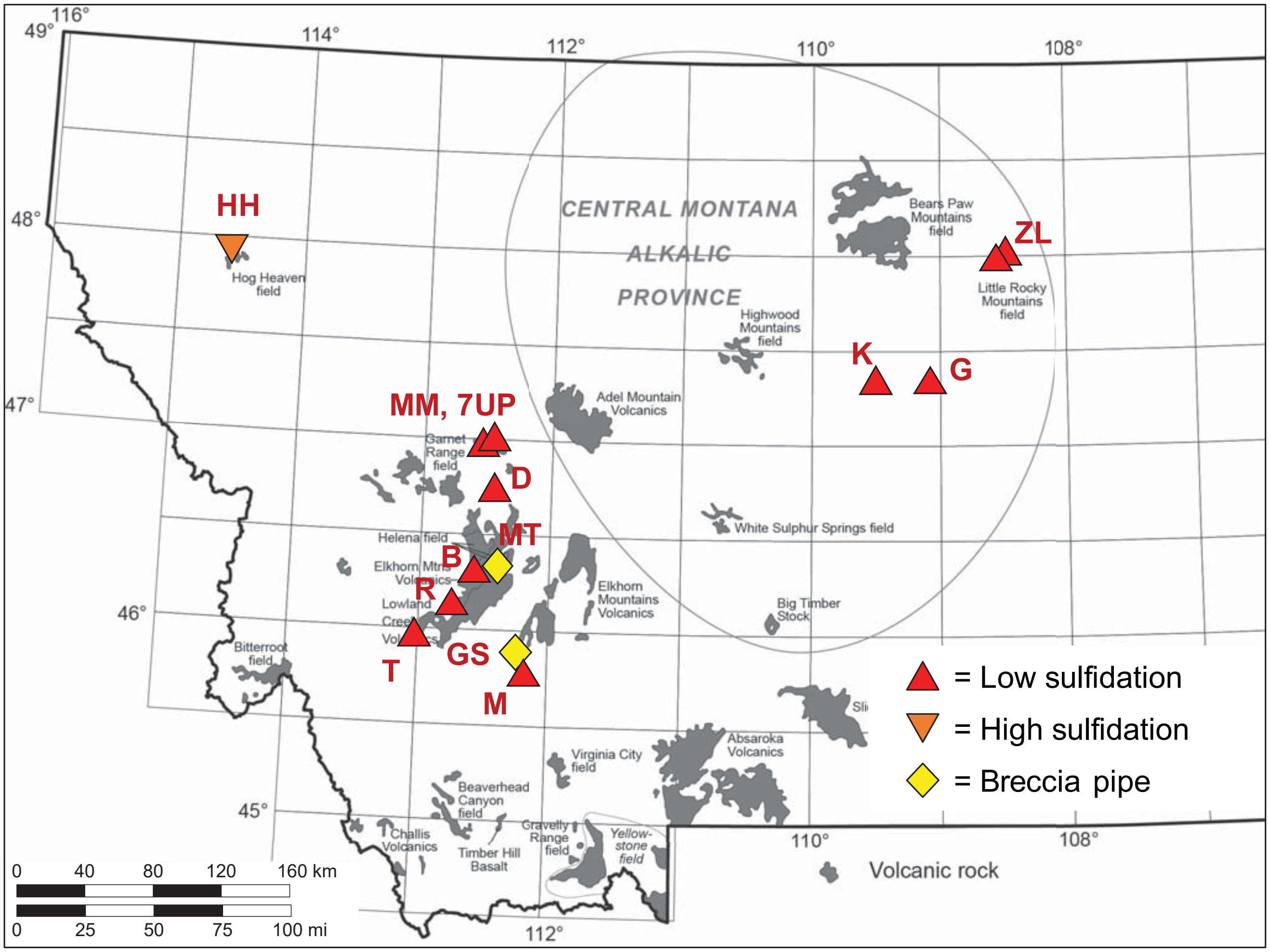


Figure 5. Epithermal gold–silver deposits of Montana. B, Basin; D, Drumlummon; GS, Golden Sunlight; HH, Hog Heaven; K, Kendall; M, Mayflower; MM, McDonald Meadows; MT, Montana Tunnels; R, Ruby (Oro Fino); 7UP, Seven Up Pete; T, Tuxedo; G, Gies; ZL, Zortman-Landusky.

Several epithermal deposits in Montana are rich in telluride minerals, including Golden Sunlight, Mayflower, Zortman–Landusky, and the Geis mine in the Judith Mountains. Previous workers have suggested that these deposits are part of a northeast-trending belt of epithermal Au and porphyry Cu-Mo deposits associated with Late Cretaceous and Tertiary alkaline magmatism. This belt of mineralization approximately coincides with the Great Falls Tectonic Zone, and is similar in some respects to the Colorado Mineral Belt.

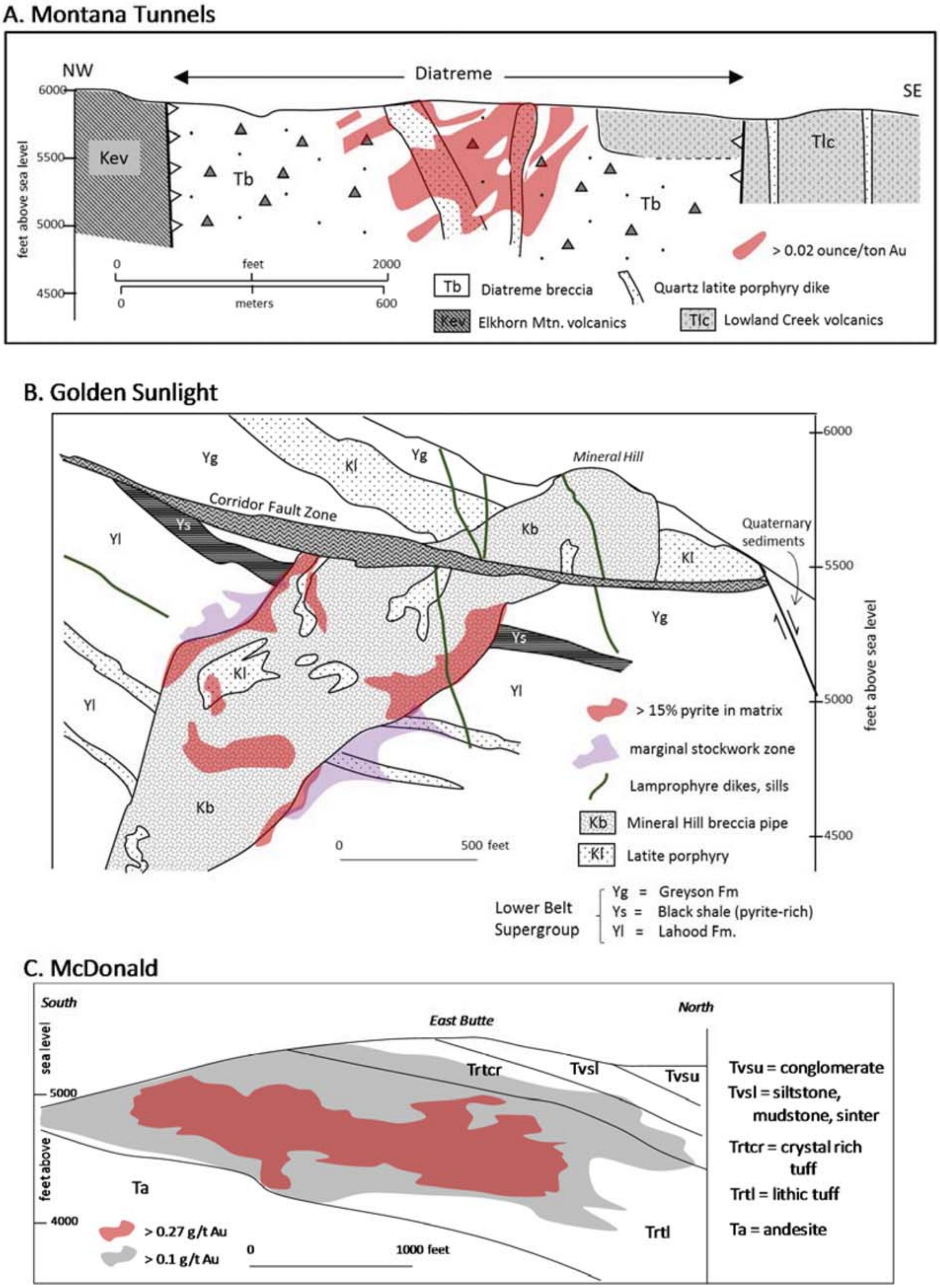
The Golden Sunlight district has produced more gold (>3 M oz) than any other deposit in Montana. Most of this gold has come from the Mineral Hill Breccia Pipe (MHBP). The MHBP is roughly 200 m in diameter, plunges west at about 50 degrees, and cuts lithic sandstone, siltite, and argillite of the mid-Proterozoic LaHood and Greyson Formations (fig. 6). The MHBP is believed to be an upper-level structure associated with a deep porphyry-Mo hydrothermal system (Spry and others, 1996). Fragments in the MHBP include hydrothermally altered latite porphyry as well as silicified Belt country rock, and the matrix of the breccia grades into latite with depth. DeWitt and others (1996) obtained an imprecise whole-rock U-Pb age of 84 ± 18 Ma for the altered latite (which they re-classified as rhyolite), and an ^{40}Ar/^{39}Ar date of 76.9 ± 0.5 Ma for biotite phenocrysts in a post-mineral lamprophyre dike. An unpublished zircon U-Pb date of 81.9 ± 1.9 Ma was recently obtained for latite associated with the MHBP (D. Odt, Barrick Gold, writ. commun., July 2017). Thus, mineralization at Golden Sunlight overlaps with emplacement of the Elkhorn Mountains Volcanics. Geologic evidence in combination with sulfur-isotope studies shows that pyrite in the Golden Sunlight deposit, as well as base and precious metals, is a mixture of Late Cretaceous magmatic/hydrothermal and Precambrian sedimentary sources (Porter and Ripley, 1985; Spry and others, 1996; Foster and others, 1999; Gnanou and Gammons, 2018).

The Montana Tunnels mine near Jefferson City is

Table 3. Summary data for epithermal Au-Ag deposits of Montana.

Deposit Name	County/ Mining District	Mineralization Style	Ore Mineralogy	Years of Recorded Production	Metal Production	Refs.
Basin Creek	Jefferson	Veins and shear zones cutting Oligocene, rhyolite dome and pyroclastic rocks.	Gold, py, asp	1892–1926; 1988–1990	~100,000 oz Au (>0.5 M oz low-grade reserve)	Teal and others, 1989
Drumlummon	Lewis & Clark Marysville District	Quartz-carbonate veins cut hornfels of Belt-aged metasediments near late Cretaceous Marysville Stock.	Gold, silver, elec, prc, tet, str, py, cpy, gal, sph	1873–1953; 2010–2013	>1.1 M oz Au and >10 M oz Ag for district, most production from Drumlummon mine	Pardee & Schrader, 1933; Walker, 1992; Griffith, 2013
Golden Sunlight	Jefferson	Pyrite-rich, Mineral Hill breccia pipe cuts Lahood and Greyson Fms., with probable Mo-Cu porphyry at depth.	Gold, elec, Au-Ag-Bi tellurides, py, cpy, tet-tnt, gal, sph, mbd	1983–2016	>3 M oz Au with byproduct Ag and Cu	Porter & Ripley, 1985; Spry and others, 1996; Oyer and others, 2014
Hog Heaven	Flathead	Veins, replacements, and hydrothermal breccias cutting Oligocene dacite–rhyolite domes, ash flows, and tuffs.		1928–1975	6.9 M oz Ag, 16,800 tons Pb, 300 tons Cu, minor Au production, but 59,000 oz Au resource	Shenon, 1935; Lange and others, 1994; Foster & Childs, 1993
Kendall	Fergus North Moccasin	Silicified karst breccia at top of Madison Limestone near contact with syenite.	Au-rich pyrite, minor thallium sulfides	1900–1942; 1988–1996	~820,000 oz Au, ~150,000 oz Ag total production + reserves	Lindsey, 1985; Kurisoo, 1991
McDonald Meadows	Lewis & Clark			Unmined	7.85 M oz Au (unmined reserve)	Bartlett and others, 1998
Montana Tunnels	Jefferson	Diatreme cutting Elkhorn Mountains Volcanics near contact with Boulder Batholith.	elec, sph, gal	1986–2010	1.7 M oz Au, 30.8 M oz Ag, 200,000 tons Pb, 550,000 tons Zn	Sillitoe and others, 1985
Zortman-Landusky	Phillips Little Rocky Mtns	Epithermal overprint on early, barren porphyry system; Tertiary syenites intruded into Precambrian metasediments.	Gold, elec, tet, py, tellurides, asp, gal, sph, cpy, mbd	1979–1988	>1 M oz Au, >5 M oz Ag production; >2.8 M oz Au resource	Wilson & Kyser, 1988; Russell, 1991; Foster & Childs, 1993

Note. Mineral abbreviations: asp, arsenopyrite; cpy, chalcopyrite; elec, electrum; gal, galena; mbd, molybdenite; prc, pearceite; py, pyrite; sph, sphalerite; str, stromeyerite; tet, tetrahedrite; tnt, tennantite.



A. Montana Tunnels

B. Golden Sunlight

C. McDonald

Figure 6. Simplified geologic cross sections through the Montana Tunnels, Golden Sunlight, and McDonald (East Butte) gold deposits. Sources of data: (A) Sillitoe and others (1985); (B) DeWitt and others (1996); (C) Bartlett and others (1998).

also a breccia pipe deposit, but is richer in Ag and base metals (Pb-Zn) than the Golden Sunlight breccia, is less silicified, and has a gangue mineral assemblage that includes carbonates (Mn-calcite, siderite) as well as quartz. Also, whereas Golden Sunlight is Cretaceous, Montana Tunnels is Eocene (Sillitoe and others, 1985). Production from the Montana Tunnels open pit from 1986 to 2010 is estimated at 1.7 M oz Au, 30.8 M oz Ag, 400 million lbs Pb, and 1.1 billion lbs Zn (Eastern Resources website, 2012). The Montana Tunnels breccia pipe includes pieces of volcanic rock and Butte Granite (as well as carbonized wood fragments) in a tuffaceous, quartz–latite matrix. The pipe is interpreted to be a diatreme emplaced near the paleosurface during eruption of the Lowland Creek Volcanics (Sillitoe and others, 1985).

Montana Tunnels is located near the northeast end of a graben that cuts the Butte Granite and that is partly filled with felsic to intermediate volcanic rocks of the Lowland Creek field (Foster, 1987). Other epithermal deposits associated with this graben include the Tuxedo mine near Butte (Scarberry and others, 2015), the Oro Fino district west of Basin (Korzeb, 2017), and the Basin Creek (Pauper's Dream) deposit north of Basin (fig. 5). Korzeb and Scarberry (2018) obtained ^{40}Ar/^{39}Ar dates of 45.8 ± 1.0 and 50.7 ± 1.2 Ma for hydrothermal sericite at Oro Fino. Although originally thought to be part of the Lowland Creek Volcanics, Teal and others (1987) reinterpreted the pyroclastic–rhyolite host rocks at Basin Creek to be Oligocene. Basin Creek was most recently mined in 1988–1990, producing 82,000 oz of gold from 3 Mt of ore at 0.033 oz/t (Teal and others, 1987). Although much gold is reported to remain in the ground at Basin Creek (Tysdal and others, 1996), it is unlikely to be mined, as the property is now being used as a mine-waste repository for the State of Montana.

The Zortman–Landusky Mines, located on the crest of the Little Rocky Mountains, were a series of open pits located 5 km apart that together produced over 1 M oz of gold between 1979 and 1998. Mineralization at the two mines is similar, and has been described as an epithermal system overprinting a syenite–porphyry intrusion that itself lacks typical porphyry-style alteration and mineralization patterns (Wilson and Kyser, 1988; Russell, 1991). Mineralization exists in the syenite and extends into basement gneiss of Archean or paleo-Proterozoic age. Ore minerals, mainly native gold, electrum, and Au-Ag-tellurides, are associated with pyrite, marcasite, arsenopyrite, minor base-metal sulfides, and fluorite (Wilson and Kyser, 1988; Foster and Childs, 1993). Epithermal mineralization is developed in breccias along high-angle faults and in stockworks on the fault margins (Russell, 1991; Foster and Childs, 1993).

A number of Au- and Ag-rich quartz veins occur in the Marysville district, roughly 30 km northwest of Helena. The largest historic producer was the Drumlummon vein, a N15°E-striking, steeply dipping lode up to 10 m wide, 1 km long, and 500 m deep (Knopf, 1913; Walker, 1992). Other lodes stemming off the Drumlummon include the North Star, Castletown, Empire, and St. Louis veins. Together, these mines produced over 1 M oz of gold and over 10 M oz of silver between 1873 and 1950 (Walker, 1992). The veins are hosted by hornfels of the mid-Proterozoic Empire and Helena Formations near their contact with the Marysville Stock, the northernmost pluton of the Boulder Batholith. In 2010, renewed exploration in the district discovered the Charly vein, a high-grade "bonanza"-style vein that was the focus of small-scale, underground mining from 2010 to 2013. The Charly vein contains abundant electrum, native silver, stromeyerite, argenite/acanthite, pearceite, and base-metal sulfides, in a gangue of quartz, chalcedony, adularia, and Mn-rich dolomite (Griffith, 2013).

The Kendall mining district, located on the east flank of the North Moccasin range about 30 km northwest of Lewistown, produced roughly 800,000 oz of gold from a series of open pits from 1900 to 1942, and again from 1988 to 1996 (Robertson, 1950; MBMG archives). Most of the gold is hosted by the Mission Canyon limestone near its contact with a Paleocene syenite–porphyry intrusion. Gold occurs as disseminations in stratabound karst breccias, in hydrothermal/intrusive breccias, in altered syenite, and in sandstone beds of the overlying Kibbey Formation (Kurisoo, 1991; Foster and Childs, 1993). The Kendall district bears certain similarities to "Carlin-type" gold deposits of the Great Basin, including carbonate host rocks, alteration consisting of silicification and carbonate dissolution, the occurrence of "invisible" gold associated with arsenian pyrite, and elevated concentrations of thallium, a trace metal that is common in Carlin-type gold deposits but otherwise is extremely rare (Ikramuddin and others, 1986).

The unmined McDonald gold deposit (also known as McDonald Meadows, fig. 6), located near the headwaters of the Blackfoot River 5 km west of the Heddleston porphyry Cu-Mo deposit, fits most of the characteristics of a typical LS style epithermal deposit. The deposit is hosted by Eocene to Oligocene felsic volcanic rocks (ash-flow tuffs), and is overlain by silica sinter that locally contains plant fossils (Bartlett and others, 1998). Gold occurs in a network of quartz–adularia and chalcedony veins that extend up into the surface sinter. The deposit contains an estimated 7.85 M oz of gold, and has been oxidized to a depth of 300–350 m. The mineralization at McDonald is low grade, averaging 0.67 g/ton (ppm) Au (Bartlett and others, 1998). At these grades, the most economically viable means of mining and milling the entire deposit is by open pit, cyanide heap-leach. However, in 1998, the people of Montana passed bill I-137, which banned open-pit, heap-leach cyanide mining, effectively halting further development at the McDonald property. The current owners of the property are attempting to define a smaller, high-grade reserve at McDonald that could possibly be mined by gravity and flotation.

The only epithermal deposit in Montana that could be put into the high sulfidation (HS) category is Hog Heaven, located 30 km west of Flathead Lake. Here, silver and lead, with lesser amounts of Au, Cu, and Zn, were mined from an area of vuggy silica and advanced argillic alteration developed at shallow level in an Oligocene dacite lava dome (Lange and others, 1994). Lange and others (1994) suggested that the Hog Heaven district represents an Ag- and Pb-rich end member among the continuum of HS epithermal deposits. However, the mine has limited vertical exposure, and others have suggested that the advanced argillic alteration at Hog Heaven might instead be a near-surface phenomenon (Rostad and Jonson, 1997). The question has exploration significance, as many HS epithermal deposits occur on top of gold-rich porphyry–Cu systems. A recent thesis by Kallio (2020) includes new mineralogy and stable isotope data consistent with the idea that the Hog Heaven mine was once underlain by a porphyry magma.

Deposits of Uranium, Thorium, and the Rare Earth Elements

An overview of uranium deposits in Montana is given by Weissenborn and Weis (1963). These deposits include: (1) uraninite in late chalcedony veins with minor silver and base metals cutting the Butte Granite of the Boulder Batholith (Becraft, 1956); (2) secondary U minerals in brecciated Madison Group limestones of the Pryor Mountains (Moore-Nall, 2016); (3) elevated but low-grade U in lignite of eastern Montana and the Dakotas (Hail and Gill, 1953; Armstrong, 1957); and (4) elevated but low-grade U in phosphatic black shale of the Permian Phosphoria Formation. The only U production in Montana has been from the first and second types listed above, and this has been minor. The Butte Granite as a whole is elevated in U and Th, which has caused problems with radon gas in homes and elevated concentrations of radionuclides in drinking water wells (Caldwell and others, 2014). Conversely, tourists can enter underground tunnels at the Merry Widow (Basin) and Free Enterprise (Boulder) "health spas" and relax in comfortable chairs while inhaling low levels of radon gas, thought by some to be therapeutic (Salak, 2004). Although small, the U deposits of the Pryor Mountains are locally of good grade, and are geologically similar to the breccia pipe hosted U deposits that cut the Redwall limestone (stratigraphic equivalent of the Madison Group) in the Colorado Plateau. Uranium-bearing breccias in the Pryor Mountains contain a number of rare secondary U minerals, including tyuyamunite (Moore-Nall, 2016).

Several occurrences of minerals rich in rare earth elements (REE) exist along the Montana–Idaho border. These deposits are associated with alkalic dikes and stocks of the western Montana–Idaho alkalic belt (Schissel, 1983; Gammons, 2020a), which extends from Lemhi Pass to the Rainy Creek Complex, host to the Libby vermiculite mine. At Lemhi Pass, thorite ($ThSiO_4$) and monazite ($CePO_4$) occur with specular hematite, barite, and biotite in veins and shear zones cutting Proterozoic metasediments (Anderson, 1961; Sharp and Cavender, 1962; Staatz and others, 1972; Gillerman and others, 2003). According to Van Gosen and others (2009), the veins of the Lemhi Pass district represent the largest thorium resource in the United States. Given that the ratio of REE to Th is roughly 1:1 in the veins, there is also a substantial amount of REE in the district. The Snowbird deposit, located in the Bitterroot Mountains 55 km west of Missoula, contains parisite ($CaCe_2(CO_3)_3F_2$) with quartz, fluorite, and ankerite in a vein cutting the Idaho Batholith. Owing to the unusually coarse-grained nature of the mineral intergrowths, the Snowbird deposit was initially thought to be a carbonatite dike (Clabaugh and Sewell, 1964). Later workers concluded that it is the product of hydrothermal fluids sourced from the Idaho Batholith (Metz and others, 1985; Samson and others, 2004). Other REE occurrences have been described in the Sheep Creek area near the headwaters of the West Fork of the Bitterroot River. Here, a set of northwest-striking quartz-carbonate pods and veins cut metasedimentary rock at a low angle. The veins are locally rich in barite, apatite, the niobium-rich minerals columbite, euxenite, and fersmite, as well as the REE-bearing minerals monazite, allanite, and ancylite (Crowley, 1960; Heinrich and Levinson, 1961; Gammons, 2020b). The literature is unclear as to whether the Sheep Creek deposits are of hydrothermal, metamorphic-segregation, or magmatic affinity.

The central Montana alkalic province, known to petrologists for its unusually diverse igneous rocks (Irving and Hearn, 2003), hosts several carbonatite bodies, the largest of which is the Rocky Boy stock of the Bears Paw Mountains. Veins associated with the Rocky Boy carbonatite locally contain up to 3.5% REE (Pecora, 1962). Other carbonatites, as well as kimberlites (including the diamond-bearing Homestead kimberlite, Hearn, 2004), can be found in the Missouri Breaks and Grass Range areas. In a recent synthesis, Duke (2009) proposed that the igneous rocks of central Montana are part of a larger, 700-km-long, N40°W-trending belt of alkaline magmatism extending from the Black Hills of South Dakota to southern Alberta that he has named the "Great Plains alkalic province." The large and possibly mineable Bear Lodge REE deposit is located in carbonatite and associated alkalic rocks in the Wyoming portion of the Black Hills (Moore and others, 2015). Although no mineable REE deposits have yet been found in the alkalic rocks of Montana, it is possible that new discoveries of this type could be made in the future.

Gold Placers

Placer gold was first reported in Montana in 1852 in alluvium along Gold Creek, Powell County (Pardee, 1951), and the significant placer deposits at Bannack were discovered in 1862, with Alder Gulch and Last Chance Gulch shortly after. Many of these early discoveries were made by miners who had rushed to the California gold fields in 1848, and then fanned out to other western territories with their newly developed exploration and mining skills (Gardner and Johnson, 1934). The volume of miners was augmented with the conclusion of the Civil War and the incredible displacement of people caused by the conflict. Placer mining required little capital but had the potential to supply a lifetime of wealth for some. Eventually, placer gold would be discovered in 30 of the 56 counties in Montana and placers are known to exist in 243 drainages (fig. 7).

Records suggest a total placer gold production in Montana of over 17,700,000 oz of gold between 1862 and 1965 (Lyden, 1948). This number is probably low, since few accurate records were kept, especially in the first few months following a new discovery. Placers, more so than lode gold deposits, yielded gold that was often not accounted for in official records. Table 4 gives a list of placer gold production by county, with major deposits named. Virginia City (Alder Gulch) was the largest producer by far, followed by Last Chance Gulch (Helena) and Confederate Gulch. Floating, bucket-line dredges were used for many of the major placer operations, including Last Chance Gulch, Gold Creek, Alder Gulch, North Meadow Creek near Ennis, and Eldorado Bar east of Helena (Jennings and Janin, 1916). Besides gold, sapphires and garnets have been recovered from placer deposits in Montana (see Berg and others, this volume), as well as minor amounts of scheelite and cassiterite.

Given the geographic distribution of placers in Montana (fig. 7), it is clear that no single geologic setting is responsible for placer gold occurrences. Significant placer gold has been found in streams draining Archean basement (e.g., Alder Gulch), Belt sedimentary rock (Confederate Gulch, Ninemile), and Paleozoic–Mesozoic metasediments near contacts with granitic intrusions (Bannack, German Gulch, Gold Creek, Last Chance Gulch). In some districts there is a clear link between placer gold and a nearby bedrock source (Woodward, 1994). For example, most of the gold in German Gulch probably came from the Beal Mountain gold–skarn deposit near the headwaters of this small creek. In other cases, the link is more mysterious, as at Bannack, Ninemile, and Alder Gulch. Alder Gulch stands out as one of the districts with the highest ratio of placer gold produced to known lode gold sources. Is this because exploration has not yet found the big lodes, or is it because the source rocks have eroded away? Other districts contain large amounts of gold in their bedrock but have produced relatively little placer gold. Examples include the Whitehall district (near Golden Sunlight, Montana's largest gold mine) and Silver Bow Creek (which drains the world-class Butte porphyry–lode deposit). Roughly 3 million oz of gold has been mined from the lode deposits of Butte, and Houston (2015) estimated that as much as 18 million

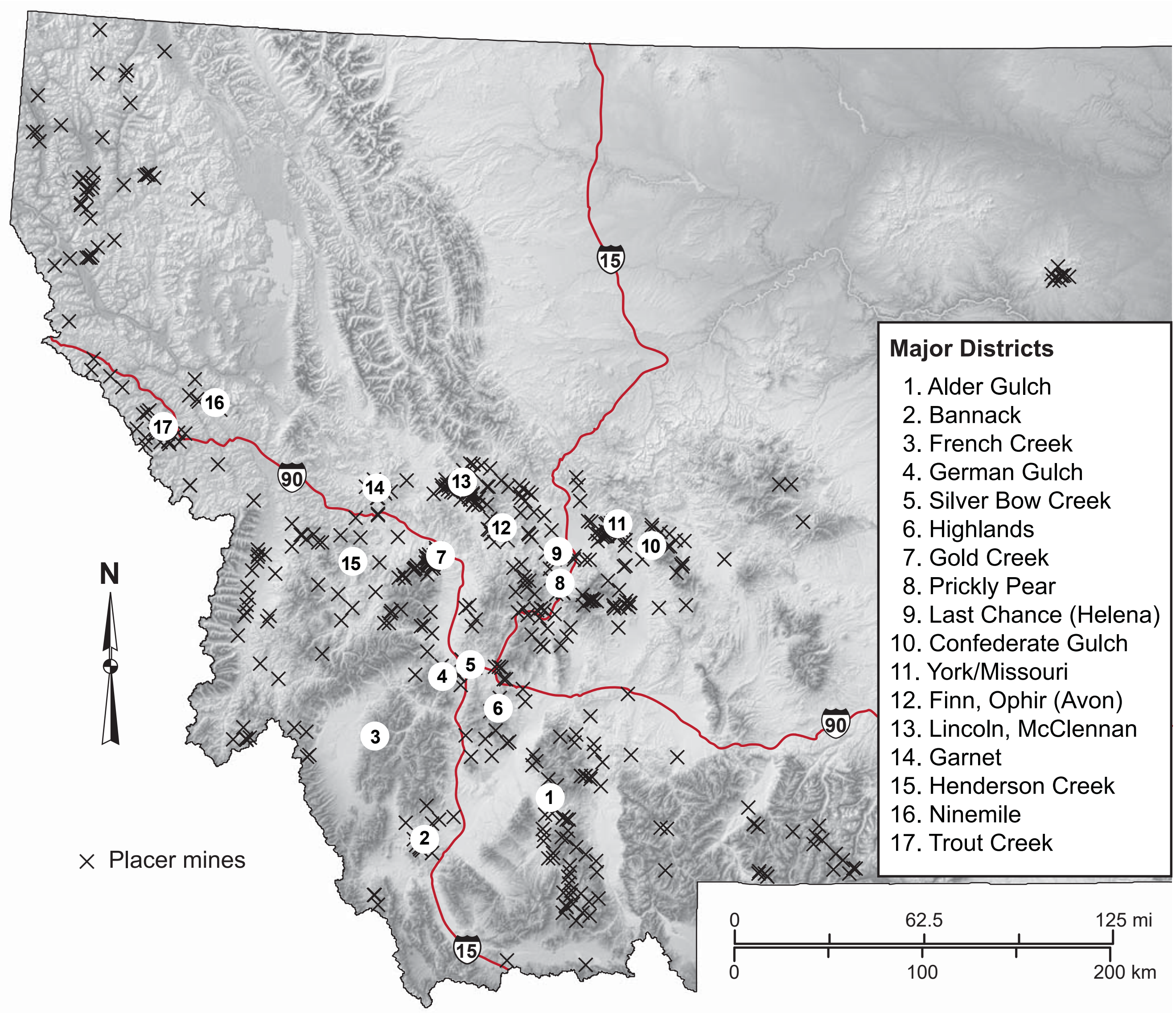


Figure 7. Location of gold–placer deposits in Montana.

oz gold might have existed as an epithermal cap on top of the Butte deposit based on a comparison with other porphyry–epithermal systems globally. By comparison, only around 120,000 oz of gold was recovered by placer diggings in Silver Bow Creek.

Although there must ultimately be a bedrock source, whether or not a good source region produces a rich placer also depends on the district's history of glaciation, mass wasting, and alluvial transport. Many rich placers in Montana were reworked multiple times by periods of alpine glaciation and outwash, debris flows, and floods. The importance of debris flows, especially in narrow drainages where there is a nick point in stream gradient, was noted by McCulloch and others (2003). Such deposits can concentrate gold and other dense minerals due to the water-saturated, turbulent nature of the flows. Transport of gold nuggets downgradient can also change the shape of the particles (Loen, 1994, 1997), as well as their fineness (percentage gold by mass). Because silver is more soluble than gold in the weathering environment, gold particles, including the rims of larger gold nuggets, tend to increase in fineness with time and transport distance (Desborough, 1970). Some placer districts were known for their exceptionally pure gold, including the Ninemile district (96–100% fine). Gold fineness is also a function of the purity of the gold in the bedrock source, which can range from Ag-rich electrum (e.g., at the Drumlummon mine in Marysville) to nearly pure gold. Lange and Gignoux (1999) cited the high purity of gold at Ninemile, in combination with the relatively short inferred distance of transport, as evidence that the source of the gold placers could be undiscovered quartz-lode deposits of the "orogenic" or "slate-belt" affinity, which typically contain free gold with high fineness.

Table 4. Gold production for major placer districts of Montana. All production data from Koschmann and Bergendahl (1968).

County	District	Stream Drainage	Recorded Placer Production
Beaverhead	Bannack	Grasshopper Creek	>132,000 oz Au (conservative estimate)
Broadwater	Confederate Gulch		580,550 oz Au
Deer Lodge	French Creek		50,000 to 250,000 oz. Au
Granite	Garnet (First Chance)	Bear Creek	260,000 to 355,000 oz Au
Granite	Philipsburg	Henderson Creek	About 80,000 oz Au, some scheelite recovered in WWII
Jefferson	Clancy	Prickly Pear Creek	Roughly 100,000 oz Au
Lewis & Clark	Helena	Last Chance Gulch	At least 940,000 oz Au
	Lincoln	Lincoln Gulch	About 342,000 oz Au
	McClennan	McClennan Gulch	About 340,000 oz Au
	Marysville	Silver Creek	164,500 oz Au
	York-Missouri River	Several drainages	>265,000 oz Au
Madison	Virginia City	Alder Gulch and tributaries	>2,475,000 oz Au
Mineral	Cedar Creek–Trout Creek		>150,000 oz. Au
Missoula	Elk Creek		52,000 to 100,000 oz. Au
	Ninemile Creek		100,000 to 120,000 oz. Au
Powell	Finn	Washington, Jefferson, Buffalo gulches	81,000 oz Au
	Ophir (Avon)	Carpenter Creek	>180,000 oz Au
	Pioneer	Gold Creek	246,200 oz Au
Silver Bow	Butte	Silver Bow Creek	120,000 oz Au
		German Gulch	about 240,000 oz Au
	Highland	Fish Creek	>50,000 oz Au

The discovery of large gold nuggets in river gravel, in addition to their monetary value, usually sparks intense mystery and excitement. Some notable gold nuggets found in Montana include: 57 oz from McClellan Creek, 27 oz from the Pineau placer at Gold Creek, 24 oz from the McFarland placer at Gold Creek, and a record 84.48 oz nugget from California Creek near Alder Gulch (New York Times, 1902; Pardee, 1951). More recently (1989), the 27.495 troy oz Highland Centennial nugget was found south of Butte. This stone, believed to be Montana's 7th largest gold nugget, is now displayed at the Mineral Museum at Montana Tech.

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