THE BERKELEY PIT AND SURROUNDING MINE WATERS OF BUTTE

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INTRODUCTION

The Butte mining district is famous for its prodigious mineral wealth (see Reed and Dilles, 2020). It is also widely known as an example of environmental damage caused by over 150 years of hard rock mining, milling, and smelting (Moore and Luoma, 1990; Dobb, 1996). These impacts extend from Butte to Missoula via the upper Clark Fork River corridor, and include over 100 km of streamside tailings washed downstream during floods, as well as the major smelting operations near the town of Anaconda. The severity of the environmental damage is episodically brought into focus by events in the news, such as the recent (November, 2016) death of over 3,000 snow geese that landed on the Berkeley Pit during their annual southward migration (Robbins, 2016). Despite the massive scale of the contamination on the Butte Hill, there have been significant reductions in risk to human and ecosystem health through ongoing cleanup efforts led by the U.S. Environmental Protection Agency (EPA), British Petroleum-Atlantic Richfield (BP-ARCO), Montana Resources (MR), and the Montana Department of Environmental Quality (MDEQ).

This chapter gives an overview of the Butte Mine Flooding Operable Unit (BMFOU), which includes the inundated Berkeley Pit and surrounding flooding underground mine workings. The paper draws on over 30 years of water-level and water-quality data collected and archived by the Montana Bureau of Mines and Geology (MBMG).

Site Overview

The general layout of major features on the Butte Hill is shown in figure 1. The Berkeley Pit, which mined copper in the upper and central part of the Butte ore body between 1955 and 1982, is now filled with acidic and metal-rich water. Surrounding and underlying the Berkeley Pit, and extending many kilometers to the north and west, is an extensive complex of abandoned underground mines, once serviced by over a hundred vertical shafts, many of which exceeded 1 km in depth. Although many of the bigger shafts still have headframes today, underground mining at Butte ceased in 1975 and the shafts and associated mine workings began flooding with groundwater when dewatering pumps were shut off in April 1982. Most of the shafts labeled in figure 1 are monitored for water levels by the MBMG, with the Anselmo, Steward, and Kelley mines sampled annually for water quality. The MBMG also samples a set of bedrock monitoring wells to the east and south of the Berkeley Pit (labeled A, B, C, D-2, E, F, G, and J in fig. 1).

Approximately 2 km east of the Berkeley Pit, the Continental Pit has been mined by MR for low-grade copper and molybdenum from early 1986 to the present day (with a suspension in production from July 2000 to November 2003). Ore from the Continental Pit is hauled to the mill where the rock is crushed and mineral concentrates containing chalcopyrite and molybdenite are recovered. Most of the volume of rock (>99%) that enters the mill is waste, and is pumped as a tailings slurry to the large Yankee Doodle impoundment, several kilometers north and uphill of the Berkeley Pit. Prior to 2019, MR's operation was a zero-discharge facility, meaning that all water on the mine property was recycled and reused. Beginning in October 2019, water from the northeast end of the active tailings impoundment has been sent to a new polishing plant and discharged into the headwaters of Silver Bow Creek near its confluence with Blacktail Creek. As of this writing, the treated water meets all State and Federal regulations for human and aquatic life.

Two other features in figure 1 include the precipitation (cementation) plant and the lime-treatment plant. The former, located near the base of the tail-

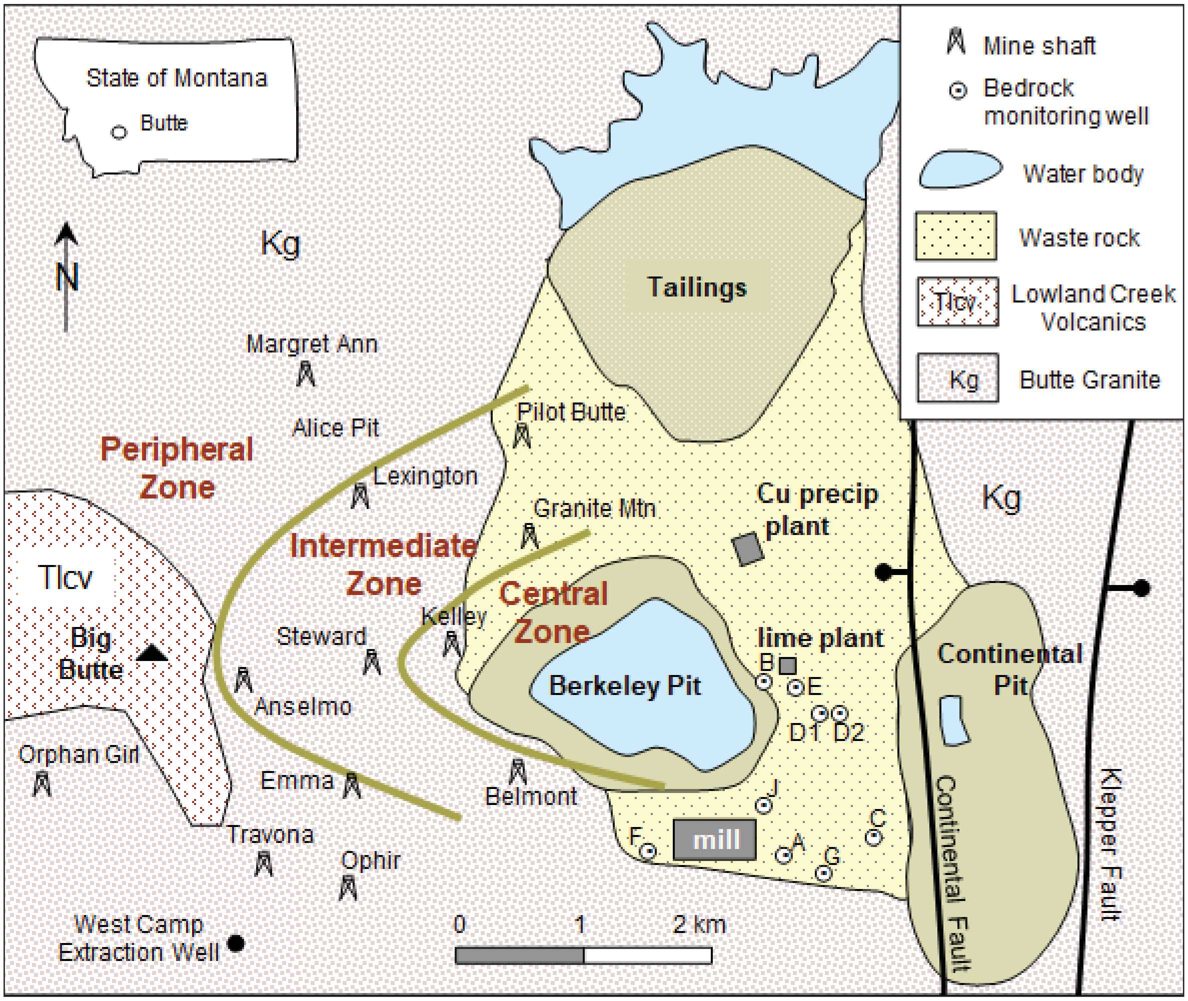

Figure 1. Map of the Butte district showing geology and mining features.

ings dam, is used to extract copper by passing acidic water over bins of scrap iron. The dissolved copper precipitates, or "cements," at the expense of the iron, and is later recovered for profit. The chemical reaction involves electron exchange, and can be written: $Cu^{2+} + Fe(s) = Cu(s) + Fe^{2+}$. When first built in the early 20th century, the precipitation plant was used to recover copper from water pumped from the underground mines. After the Berkeley Pit opened, the plant received acidic, Cu-rich water from heap leach pads and also from seeps near the base of the tailings dam [referred to as Horseshoe Bend (HSB) springs], along with the pumped underground mine water. After the Berkeley Pit closed, water from the pit lake has intermittently been passed through the precipitation plant to recover copper, along with water from HSB springs (see timeline, below).

The Horseshoe Bend lime-treatment plant, located near the east rim of the pit lake, is used to treat acidic water for use in the mine operations. From November 2003 to May 2019, this facility collected and treated acidic drainage from HSB. Hydrated lime ($Ca(OH)_2$) is stored in two large silos, and is slowly added to the influent water to raise the pH and precipitate out dissolved metals. The metal precipitates, referred to as "sludge," are discharged back to the Berkeley Pit, where many of the solids re-dissolve, effectively neutralizing some of the acidity of the pit lake. Fifteen years of sludge disposal has had a significant impact on the total acidity and pH of the lake (Duaime and others, 2019a; Gammons and Icopini, 2019). Since September 2019, HSB water has been pumped directly to the Yankee Doodle tailings impoundment for co-disposal with mill tailings, and the lime plant switched to treating Berkeley Pit water full time. Sludge from the lime treatment is still being discharged to the pit, and the treated water is used by the active mine and mill.

Previous Studies

Beginning in 1987 (Sonderegger and others, 1987), and annually since 1998 (Duaime and others, 1998), the MBMG publishes an update and interpretative report on water levels and water chemistry in the BMFOU (Duaime and others, 2019a, and references therein). Most of these reports are available on the internet through the MBMG Publications Catalog (http://www.mbmg.mtech.edu/). Raw data can be found at the MBMG's Groundwater Information Center (GWIC) website. In addition, a list of journal papers and student theses dealing with the Berkeley Pit lake, the Continental Pit lake, the Yankee Doodle tailings pond, and the flooded underground mine workings is given in table 1. Selected publications by the US-EPA are also listed in table 1, including the 1994 Record of Decision (ROD), the 2002 Consent Decree, and two of the more recent "Five-Year Reviews."

The low pH and unusually high concentrations of dissolved metals in the Butte mine waters were recognized and scientifically investigated as early as the beginning of the 20th century. Stone (1909) and Febles (1913) first described the cementation process at Butte whereby copper could be extracted by passing the mine water over scrap iron. Weed (1912) and Hodge (1915) gave additional descriptions of the chemistry of the mine waters being pumped out of the underground workings. It would be more than 70 years before the next generation of scientific reports on the mine waters of Butte was published (table 1).

HISTORY OF MINE FLOODING

In order to mine the Butte mineral deposit, enormous volumes of water (roughly 5,000 gallons per minute, gpm) had to be continuously pumped out of the workings. After consolidation of the underground mines by the Anaconda Company, mine workings were interconnected to drain water to central pump stations to improve efficiency (Daly and Berrien, 1923). The High Ore mine served as the central pump station from 1901 to 1967, when the pump station was moved to the Kelley mine. Once the water reached the surface, it was routed to the precipitation plant for copper recovery and then discharged to Silver Bow Creek (SBC). The practice of discharging untreated, acidic, metal-laden water to SBC continued until the late 1950s, at which time the Anaconda Company began adding lime to the water to raise the pH and reduce the mineral content of the water (Spindler, 1977). On April 22, 1982, the mine-dewatering pumps were turned off, and the vast complex of underground workings began to flood (see timeline in table 2). The first 2 yr of mine flooding were especially complex (Metesh, 2006). In the first few months, water levels in the underground mine shafts rose hundreds of feet. Also, beginning in the summer of 1983, acidic seepage from the Horseshoe Bend area, South East Berkeley, and leach pads was diverted into the Berkeley Pit, which contributed to the rise in water level. In November 1983, the water level in the Kelley mine reached the same elevation as the bottom of the open pit, and the Berkeley Pit lake was born. Sometime in early to mid-1984, the pit became the lowest point in the flooded mine system, allowing water from the underground mines in all directions to flow towards the pit (Duaime and McGrath, 2019). As a consequence of this reversal in flow direction, several of the mine shafts to the west of the Berkeley Pit showed a dramatic improvement in water quality during the period 1982–1986 (Metesh, 2006).

Table 1. Summary of literature on Butte mine waters.

MBMG Reports	**Flooded Mine Shafts**
Duaime and others, 2019	Weed, 1912
(and references therein, including	Hodge, 1915
Sonderegger and others, 1987;	Metesh, 2004, 2006
Duaime and Metesh, 2003a;	Pellicori and others, 2005
Duaime and others, 1998, 2004)	Gammons and others, 2006a
Berkeley Pit Lake	Roesler and others, 2007
Davis and Ashenberg, 1989	Snyder, 2008
Robins and others, 1997	Gammons and others, 2009
Jonas, 2000	Petritz and others, 2009
Newbrough and Gammons, 2002	Thornton and others, 2013
Madison and others, 2003	Schmidt, 2017
Gammons and others, 2003	
Maest and others, 2004	**Yankee Doodle Tailings Pond**
Pellicori and others, 2005	Berzel, 2017
Gammons and Duaime, 2006	
Twidwell and others, 2006	**EPA Documents**
Cameron and others, 2006	Record of Decision: EPA, 1994
Tucci, 2006	Consent Decree: EPA, 2002
Tucci and Gammons, 2015	5-Year Reviews: EPA, 2011, 2016
Duaime and Smith, 2018	
Duaime and others, 2019	**Useful Websites**
Gammons and Icopini, 2019	Pitwatch.org
Continental Pit Lake	Groundwater Information Center (GWIC):
McGivern, 2014	https://mbmggwic.mtech.edu/

Table 2. Timeline of significant events during mining and flooding of the Berkeley Pit lake.

Date	Description
1-July-55	Mining of Berkeley open pit porphyry copper deposit begins.
May-63	Weed Concentrator built: tails sent to Yankee Doodle Tailings pond.
1966-1967	Kelley Mine central pump station built on 3800 level; replaces High Ore 3800 station.
1-Jan-80	Mining of Continental open pit porphyry copper–molybdenum deposit begins.
22-Apr-82	Kelley Mine dewatering pumps shut off; mine flooding begins.
30-June-82	Mining of Berkeley Pit ceases; Horseshoe Bend flow (HSB) diverted to Berkeley Pit.
30-June-83	Mining of Continental Pit suspended. Water from leach pads, precipitation plant, and Continental Pit diverted to Berkeley Pit.
July-86	MR resumes mining of Continental Pit and heap leaching of old Berkeley Pit waste rock.
Apr-96	HSB is diverted away from Berkeley Pit and is pumped to tailings pond.
1998	MR ceases heap leaching operations.
Aug-98	MR begins pumping of Berkeley Pit water for copper recovery.
29-Sep-98	Major landslide on SE highwall of Berkeley Pit. 1.3 M cubic yards material slides into the lake and raises lake level 2.5 ft. Probable lake turnover.
30-Jun-00	MR suspends mining operations due to rising electricity costs. HSB diverted to pit lake. Copper recovery suspended.
Nov-03	MR resumes mining of Continental Pit.
17-Nov-03	Horseshoe Bend lime treatment plant online. HSB water is treated and the water is recycled by the mine. High-density sludge is dumped back into Berkeley Pit.
Jan-04	MR resumes pumping of Berkeley Pit water for copper recovery.
Jan-10	Copper recovery causes pit lake to shift from meromictic to holomictic state.
Nov-12	Landslide damages sample boat and boat dock, forcing the cancellation of fall pit sampling/monitoring activities.
Feb-13	Major landslide in SE corner of pit damages copper recovery pipeline; MR suspends copper recovery from Berkeley Pit. Safety concerns force MBMG to suspend Berkeley Pit sampling/monitoring activities. Lime treatment of HSB water continues, with sludge disposed in pit.
Nov-Dec-16	Approximately 10,000 snow geese land on the pit lake, resulting in over 3000 fatalities.
July-17	First successful deployment of drone boat for vertical profiling and water sampling of Berkeley Pit lake.
26-Sep-19	Lime treatment of Berkeley Pit begins. Sludge returned to pit. Treated water used by mine. HSB pumped directly to YDTP for co-disposal with mill tailings.
Oct-19	Discharge of treated mine water to Silver Bow Creek begins.

Since January 1984, the elevation of the surface of the Berkeley Pit lake has crept steadily upwards (fig. 2). Despite this trend, the Berkeley Pit lake marks the lowest point in the water table in the Butte Summit Valley, with the exception of the bottom of the active Continental Pit. All bedrock groundwater in the vicinity of the mine flows into the Berkeley Pit, not the other way around. In their 1994 Record of Decision and 2002 Consent Decree, the U.S. EPA mandated that the elevation of groundwater in nearby mines and bedrock wells must be kept below 5,410 ft above mean sea level (USGS NGVD 29), meaning the Berkeley Pit would remain the lowest point in the groundwater system. This elevation—the so-called critical level—is roughly 50 ft below the height of the alluvial water table adjacent to the pit. The 2002 Consent Decree established 14 points of compliance (POC; 7 underground mines and 7 bedrock groundwater monitoring wells). As long as the elevations of the POC sites are maintained below 5,410 ft, there is no possibility of mine water percolating through the bedrock or alluvial aquifers to discharge to SBC. At the time of this writing, the elevation of the highest point of compliance (the Pilot Butte mine shaft) is 5,381 ft. To keep the rising mine-shaft water from reaching the critical level, water in the lake will need to be pumped, treated with lime, and either discharged to SBC or reused by the active mine operation. This "pump-and-treat" process will need to be carried out in perpetuity, or until the water quality of the Berkeley Pit improves to the extent that it no longer presents a threat to the local groundwater and surface water. Beginning September 2019, MR

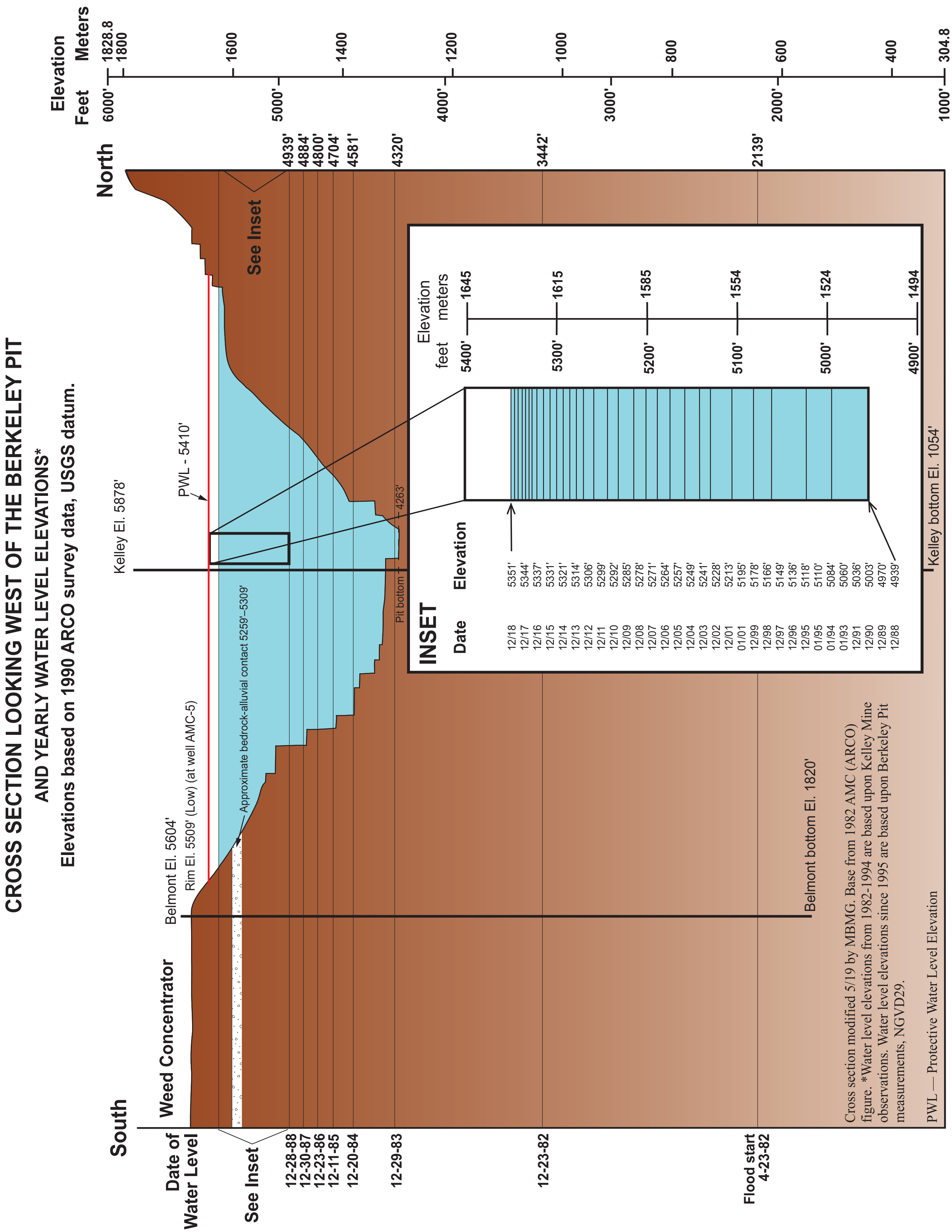

Figure 2. Rate of water-level rise in the Berkeley Pit lake and subjacent mine shafts.

and AR began operation of a pump and treat discharge Pilot Plant. Water from the Berkeley Pit is pumped to the precipitation plant for copper removal, then to the HSB water treatment plant for further neutralization and metals removal, and then pumped to the Yankee Doodle Tailings Impoundment (YDTI), where it is allowed to mix with other mine waters. Water from the YDTI is then diverted to the Pilot Treatment Plant for polishing and then discharged to SBC. Approximately 4–5 million gallons per day of water is currently being pumped from the pit; this volume appears to be stabilizing water levels in the Berkeley Pit and POC sites (Duaime, 2020).

THE BERKELEY PIT LAKE

The Berkeley Pit currently contains a lake that measures 1.3 by 1.9 km in area, is over 240 m (roughly 800 ft) deep, and contains an estimated 1.87 x 10^{11} L (4.95 x 10^{10} gallons) of acidic water. The chemistry of the Berkeley Pit has been studied for over 30 yr. The Montana Bureau of Mines and Geology has conducted most of the pit lake sampling and depth profiling, and the MBMG's Groundwater Information Center (GWIC) is the main repository for data on the pit lake. The MBMG has collected water samples from the pit over 70 times since 1984, and representative samples have been sent to dozens of laboratories around the U.S and other countries for scientific study (Duaime and others, 2019b). From 2001 to 2012, the lake has been sampled at least twice a year by the MBMG at a number of depths from surface, straddling any chemoclines detected by depth profiling of parameters such as temperature, specific conductivity, pH, ORP, dissolved oxygen, and turbidity. In the past, sampling has been done from a boat positioned near the center of the lake. However, due to a series of landslides in 2012 and 2013, it was eventually deemed too risky for scientists to navigate the lake by boat. Between 2013 and 2015 no samples were collected, and only a few grab samples of lake water were taken from the shoreline in 2016. In July 2017, a remotely operated "drone" boat designed by Montana Tech and the MBMG was used to collect water samples to a depth of 125 ft and a datasonde profile from surface to a depth of 700 ft, the first such profile collected in over 4 yr. Beginning in the fall of 2017, and semi-annually since that time, water-column profiles and samples have been collected to a depth up to 450 ft (Duaime and McGrath, 2019).

The chemistry of the Berkeley Pit lake is famously acidic, with pH levels on most visits prior to 2015 in the range of 2.5 to 2.8. More recently (by 2018), the lake had an increase in pH to about 3.8 to 4.1, where it has remained at the time of this writing. The source of the acidity in the lake is oxidation of pyrite and other acid-generating sulfide minerals in the Butte ore body. Post-mining exposure of these sulfide minerals to air and water generates sulfuric acid that breaks down minerals in the wall rock, releasing metals, sulfate, and rock-forming elements into the lake. A recent chemical analysis for the surface of the lake collected in May 2017 is given in table 3. The dominant cations are Al^{3+}, Ca^{2+}, Mn^{2+}, Mg^{2+}, and Zn^{2+}, and by far the dominant anion is sulfate. A number of other metals in the lake have concentrations that are much higher than natural surface water, including cadmium, copper, nickel, uranium, and the rare earth elements (e.g., Ce, La, Nd, Pr: see Gammons and others, 2003, for a discussion of REE and uranium in the Berkeley Pit). Prior to 2010, ferric iron (Fe^{3+}) had concentrations in the hundreds of milligrams per liter, with 400 to 600 mg/L of ferrous iron (Fe^{2+}) at depth. This situation changed in the past 5 to 10 yr, with a massive precipitation of ferric iron minerals (Tucci and Gammons, 2015), a rise in pH from 2.6 to >4.0, and a drop in total dissolved Fe concentration to <10 mg/L (Gammons and Icopini, 2019). Sometime between February 2013 and February 2016, the color of the pit lake changed from red-brown to green (fig. 3). The former reddish color was due to an abundance of dissolved and suspended ferric iron. The cause of the greenish color at present has not been determined, other than the fact that almost all of the iron (both ferric and ferrous) has precipitated and settled out of the water column.

Figure 4 summarizes some of the physical, chemical, and biological factors that influence the lake. Since the beginning of mine flooding, the lake has had no outlet, either by surface water or by groundwater leakage. Due to Butte's semi-arid climate, evaporation exceeds precipitation by about a factor of two. Thus, shallow water in the lake tends to become evaporated, a process that is best seen by shifts in the lake's H- and O-isotope signature (Pellicori and others, 2005; Gammons and others, 2006b). The pit is being filled mainly from groundwater from the subjacent underground mine workings and the fractured bedrock aquifer. A lesser amount of groundwater enters from the shallow alluvial aquifer (pre-mining SBC valley) along the east and south sides of the pit. The pit has intermit-

Table 3. Chemistry of selected mine waters of Butte (concentrations are for dissolved solutes).

Site	GWIC ID	Sample Date	Water Temp[1]	Field pH	Field SC[2]	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Fe mg/L	Mn mg/L	SiO_2 mg/L	HCO_3 mg/L	SO_4 mg/L	Cl mg/L	F mg/L
B-Pit Surface	120678	5/09/17	12.9	3.48	7,530	434	558	71	11	8.1	268	113	0	7,030	20	40.2
H-shoe Bend	125744	6/29/17	14.6	3.06	5,720	445	342	76	8	299	115	78	0	4,850	12	10.0
Tailings Lake	139260	12/4/12	1.4	10.40	2,110	426	1	95	35	<0.04	<0.01	13	2	1,190	14	1.6
Kelley	4514	5/24/17	29.8	4.54	6,460	507	326	74	52	1,050	144	77	26	4,680	27	8.4
Steward	4765	5/26/17	28.2	5.59	3,820	539	169	49	33	298	40.7	48	227	2,590	50	1.9
Anselmo	4768	5/26/17	15.4	6.06	2,300	349	99	47	14	30.0	12.0	26	390	1,070	53	0.5
Pilot Butte	139286	5/24/16	17.4	5.52	3,680	525	182	37	20	132	126	44	193	2,390	23	1.4
Travona	4782	5/24/17	13.4	6.45	1,430	197	54	38	6	0.3	4.4	20	418	346	102	0.3
Emma	4818	6/12/17	17.3	6.61	1,530	200	61	43	7	0.4	6.1	21	535	341	77	0.4
Ophir	142793	5/24/17	11.6	6.15	753	92	27	22	4	3.5	9.4	18	249	171	32	0.4
Orphan Boy	4822	5/18/17	27.5	6.38	1,630	182	49	105	7	<0.04	4.1	25	931	169	18	0.6

Site	Al µg/L	As µg/L	Cd µg/L	Co µg/L	Cu µg/L	Mo µg/L	Ni µg/L	Pb µg/L	Sr µg/L	U µg/L	Zn µg/L	Ce µg/L	La µg/L	Nd µg/L	Pr µg/L
B-Pit Surface	312,000	5	2,000	1,640	59,100	1.8 J	1,220	30	1,130	731	582,000	746	261	432	78
H-shoe Bend	240,000	2.1 J	811	826	20,600	<1	580	<0.6	821	277	235,000	419	104	252	55
Tailings Lake	37	7	<0.25	<0.25	10	1,465	7	<0.15	1,880	<0.25	<1	<0.3	<0.3	<0.3	<0.3
Kelley	15,000	10,080	24	502	87	6	284	5	757	9	197,000	23	6	21	3.2 J
Steward	722	2718	<1	94	12 J	<1	46	<0.6	1,980	4 J	50,700	<1	<1	<1	<1
Anselmo	<5	211	2	7	6	1.1 J	7	<0.15	3,830	20	7,630	<0.3	<0.3	<0.3	<0.3
Pilot Butte	98 J	1,000	<1	38	<5	<1	36	<0.6	4,440	21	20,200	<1	<1	<1	<1
Travona	<5	58	<0.25	<0.25	<1.2	<1	0.6 J	<0.15	1,350	18	13	<0.3	<0.3	<0.3	<0.3
Emma	<5	11	<0.25	<0.25	4.6 J	<1	<0.25	<0.15	1,610	18	34	<0.3	<0.3	<0.3	<0.3
Ophir	<5	4	<0.1	1	<0.5	1	0.3 J	<0.06	433	10	23	0.5 J	0.3 J	0.3 J	<0.1
Orphan Boy	<5	4	<0.25	<0.25	<1.25	<1	<0.25	<0.15	4,500	26	15	<0.3	<0.3	<0.3	<0.3

[1]Degrees C
[2]Specific conductance in µS/cm
Note. J, near detection limit; n.a., not analyzed.

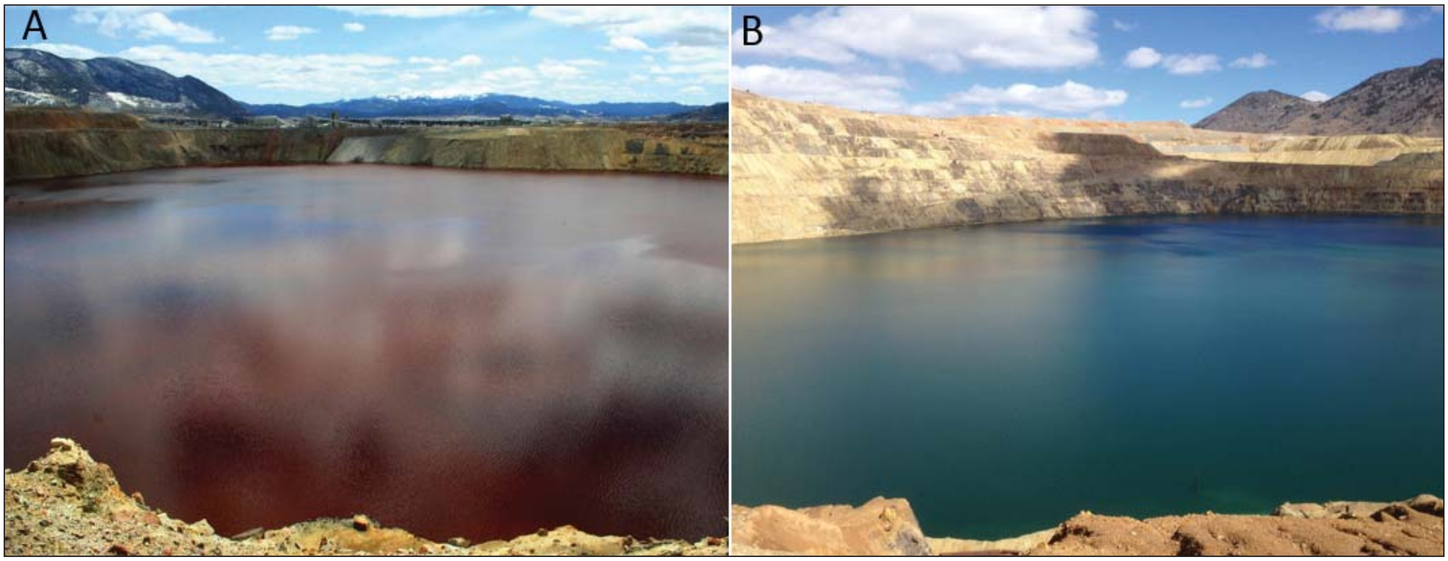

Figure 3. Photographs of the Berkeley Pit taken in (A) March 2009 (looking south) and (B) March 2016 (looking north).

tently been used as a disposal site for surface waters associated with the mining operations. The Anaconda Company diverted water from the HSB, leach pads, precipitation plant holding ponds, and East Berkeley Pit area into the pit between 1982 and 1983. Some of these flows were significant (>10,000 gpm) for short periods of time, while others were more long-lasting with flows between 2,000 and 5,000 gpm. Water from the HSB area continued to flow to the pit until mid-April 1996, when it was diverted to the Yankee Doodle tailings dam for incorporation in the mining operations. HSB water was again allowed to flow to the pit between July 2000 and November 2003 when MR suspended mining operations. When MR resumed mining in November 2003, HSB water was diverted away from the pit and to the newly constructed water treatment plant. Between 2003 and 2019, the HSB flow was collected and treated with lime prior to reuse by the active mining operation. Alkaline sludge produced as a byproduct of high-density sludge lime treatment was discharged to the pit (fig. 4). Since mid-2019, the HSB flow has been pumped directly to the Yankee Doodle tailings impoundment for co-disposal with mill tailings.

The limnology of the Berkeley Pit lake is a moving target. Conditions described in a given year may no longer be applicable only a few years later. For example, in its 36-yr history, the pit lake has switched from being holomictic (seasonally mixed) to meromictic (permanently stratified) and back again several times (Gammons and Duaime, 2006). This has depended on whether or not the less concentrated HSB flow was allowed to dump into the lake (a process that tends to stratify the lake), and also on periodic landslide events that vertically mix the lake. Another process that has had a major influence is copper recovery. During August 1998 to June 2000, and again from January 2004 to February 2013, water from the deep pit lake was pumped to the copper precipitation plant (fig. 1). In several hours of contact time, most of the dissolved Cu^{2+} would plate out on the scrap iron as elemental copper, evolving Fe^{2+} as a byproduct. The Cu-depleted and Fe-enriched water was then returned to the surface of the pit. During the more recent copper-recovery cycle, approximately 1.3 pit lake volumes were cycled through the precipitation plant. Figure 5 shows changes in the concentration of total dissolved iron as a function of depth and time from 2002 to 2017. Because so much pit water was being circulated through the precipitation plant, the chemocline separating the Fe-poor mixolimnion (shallower water) and the Fe-rich monimolimnion (deeper water) was steadily drawn down until it completely disappeared near the end of 2009 (Tucci and Gammons, 2015). Since 2010, the lake has been holomictic, with seasonal (e.g., spring and fall) turnover events (fig. 4).

The combination of vertical mixing due to copper recovery and disposal of alkaline sludge into the pit resulted in a significant increase in pH and the oxidation and precipitation of over 2 x 10^8 kg of iron in the form of the secondary ferric minerals (schwertmannite and jarosite), which settled to the bottom of the lake (Tucci and Gammons, 2015). Recent MBMG measurements in November 2019 showed pH values in the range of 4.0–4.1 from top to bottom of the water column, more than a full unit higher than pH values measured prior

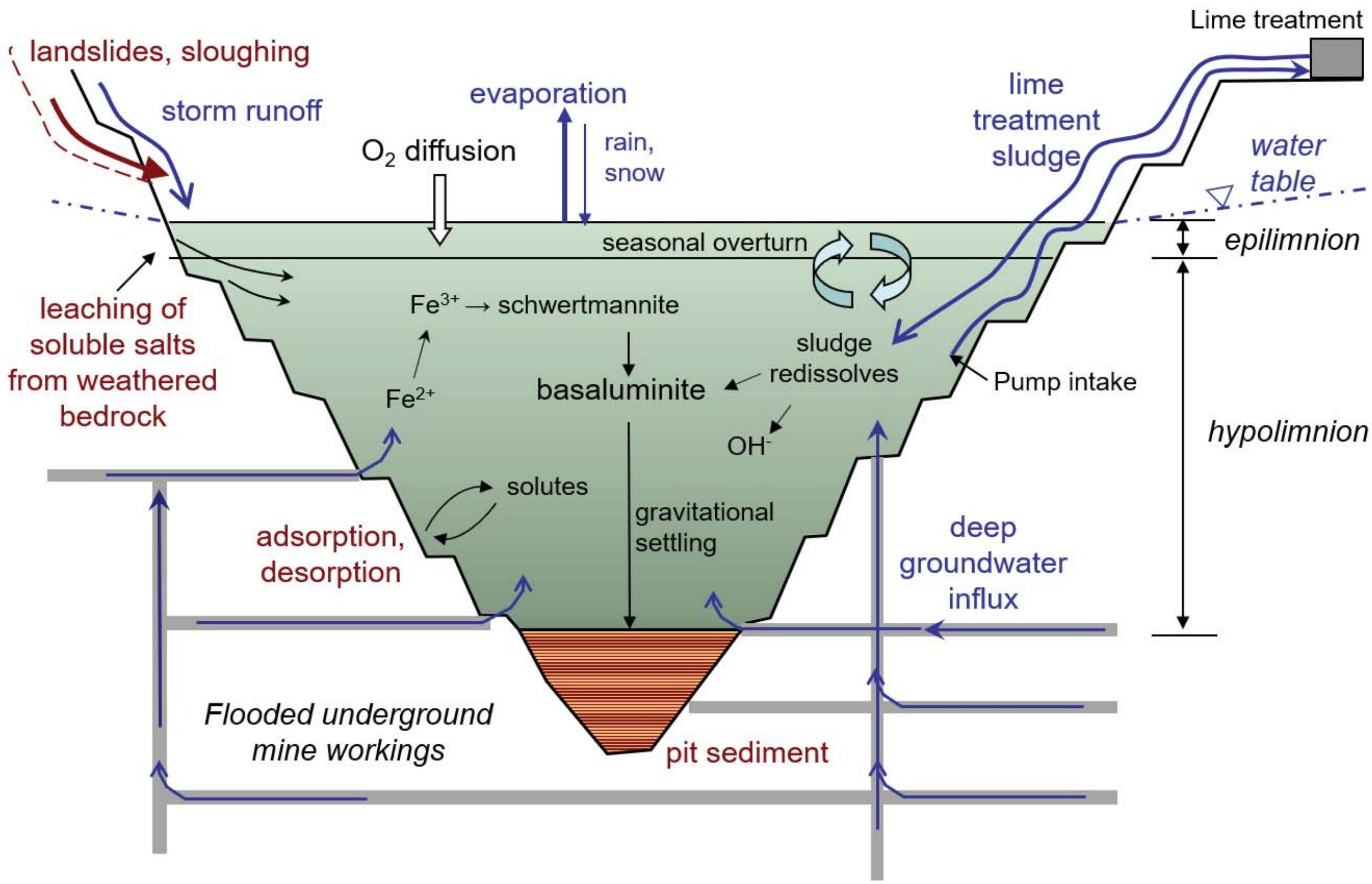

Figure 4. Schematic (not to scale) diagram showing processes influencing the chemistry of the Berkeley Pit.

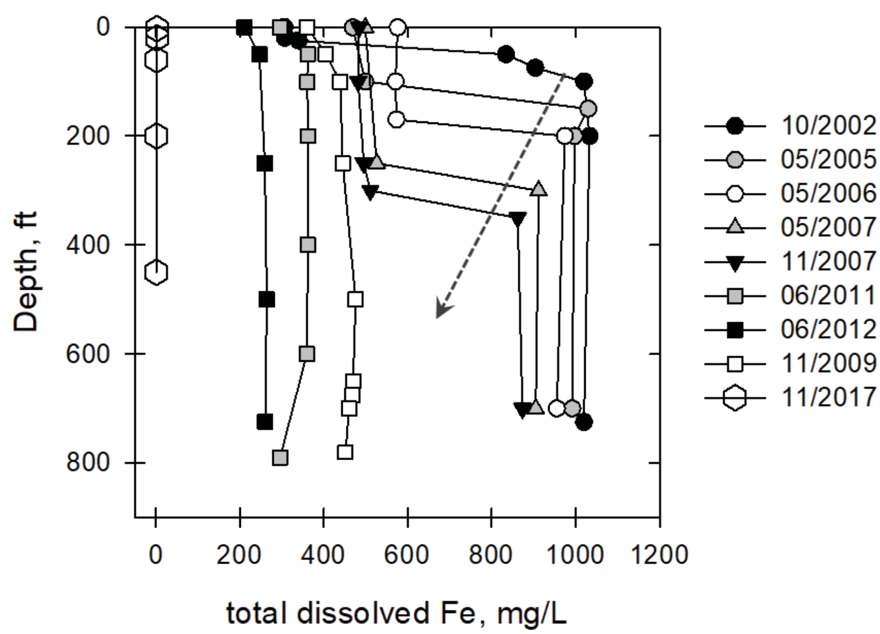

Figure 5. Changes in the concentration of total dissolved Fe in the Berkeley Pit vs. depth and vs. time. The dashed arrow shows the position of the chemocline, which completely disappeared by November 2009.

to 2010. Most of the increase in pH is attributed to addition of lime-treatment sludge (Gammons and Icopini, 2019), although investigations are ongoing. As the pit lake expands, it is encountering more of the Butte Granite that is relatively unaltered and unmineralized, as well as alluvial gravels that contain minor amounts of calcite as caliche cement. In addition, significant amounts of alluvium have sloughed into the pit lake. Interaction of pit water with these geologic materials could be another mechanism to explain a long-term rise in pH of the lake.

Biology of the Pit Lake

The Berkeley Pit lake contains abundant microbial life (Mitman, 1999). Most if not all of these microorganisms are acidophiles, meaning that they have evolved mechanisms to survive in low-pH water with high concentrations of toxic metals. In 2001, researchers at Montana Tech discovered an aquatic insect—the water boatman (family Corixidae)—swimming in shallow water along the shore of the lake (Montana Standard, April 22, 2001), possibly eating algae and other microbes. Later research at Montana Tech explored the feasibility of using algae to remediate the pit waters, but concluded that the possible benefits were outweighed by the cost of nutrient addition (Bartkowiak and Mitman, 2002; Tucci, 2006). Philip (1999) searched for the presence of sulfate-reducing bacteria in the pit sediment but found no living cells, possibly due to the high concentrations of heavy metals, including Cu^{2+} and Zn^{2+}, which are toxic to most strains of sulfate-reducers (Poulson and others, 1997). This is consistent with examination of sediment core from the pit, which showed no mineralogical evidence of a zone of sulfate reduction to a depth of at least 3 ft (Twidwell and others, 2006).

The Berkeley Pit has gained worldwide notoriety for the episodic deaths of large numbers of aquatic birds, in particular migrating snow geese (*Anser caerulescens*). Large flocks of these birds sometimes land on the water and remain for periods exceeding 24 h due to adverse weather conditions. In the worst such incident, an estimated 3,000 to 4,000 snow geese perished after prolonged exposure to the pit waters in December 2016 (Montana Standard, April 18, 2017). The exact cause of death is uncertain, although biopsies showed that the birds' internal organs were partly corroded. Research is ongoing to better understand how birds of many species interact with the pit with a view to adaptive management of the site (Capoccia and others, 2020). Stierle and Stierle (2005, 2013) have been conducting promising research on the possible medicinal value of unique, secondary metabolites isolated from the Berkeley Pit water. One of these compounds, termed Berkelic acid, has shown selective activity against ovarian cancer (Stierle and others, 2006).

To date there have been no published investigations of the microbial populations of the Berkeley Pit using modern methods of genomic analysis. Schmidt (2017) conducted a reconnaissance study of microbe populations in several of the flooded mine shafts of Butte.

FLOODED UNDERGROUND MINE WORKINGS

A labyrinth of over 15,000 km of horizontal drifts and vertical shafts underlies the Butte Hill (fig. 6; Duaime and others, 2004). When the dewatering pumps for the mine complex were turned off in April 1982, these workings began to fill with water. Hydrogeologically, the flooded mine complex can be divided into the East Camp, the West Camp, and the Outer Camp (Duaime and others, 1998). The East Camp, which includes most of the early copper-producing mines in the district, drains to the Berkeley Pit. The West Camp mine pool is controlled by continuous (since 1996) pumping of an extraction well connected to the underground workings of the Travona mine (Duaime and others, 2016). The pumped water is mixed with contaminated alluvial groundwater and, after lime treatment, is discharged to Silver Bow Creek. The Outer Camp includes a number of smaller underground mines peripheral to the main district, such as the Orphan Boy/Orphan Girl complex west of Montana Tech, and the Marget Ann mine north of the old Alice Pit at the top of the Butte Hill.

The geochemistry of the flooded underground mine workings varies considerably from shaft to shaft (table 3). All of the East Camp mines are weakly to strongly acidic, with high concentrations (tens to hundreds of milligrams per liter) of dissolved iron, manganese, and zinc (table 3, fig. 7). In general, the water quality worsens with increased proximity to the Berkeley Pit. Thus, the Kelley mine, the closest shaft to the pit that is regularly sampled by the MBMG, has the lowest pH and highest metal concentrations of any of the mine shafts on the Butte Hill. At the other end of the spectrum, the flooded West Camp and Outer

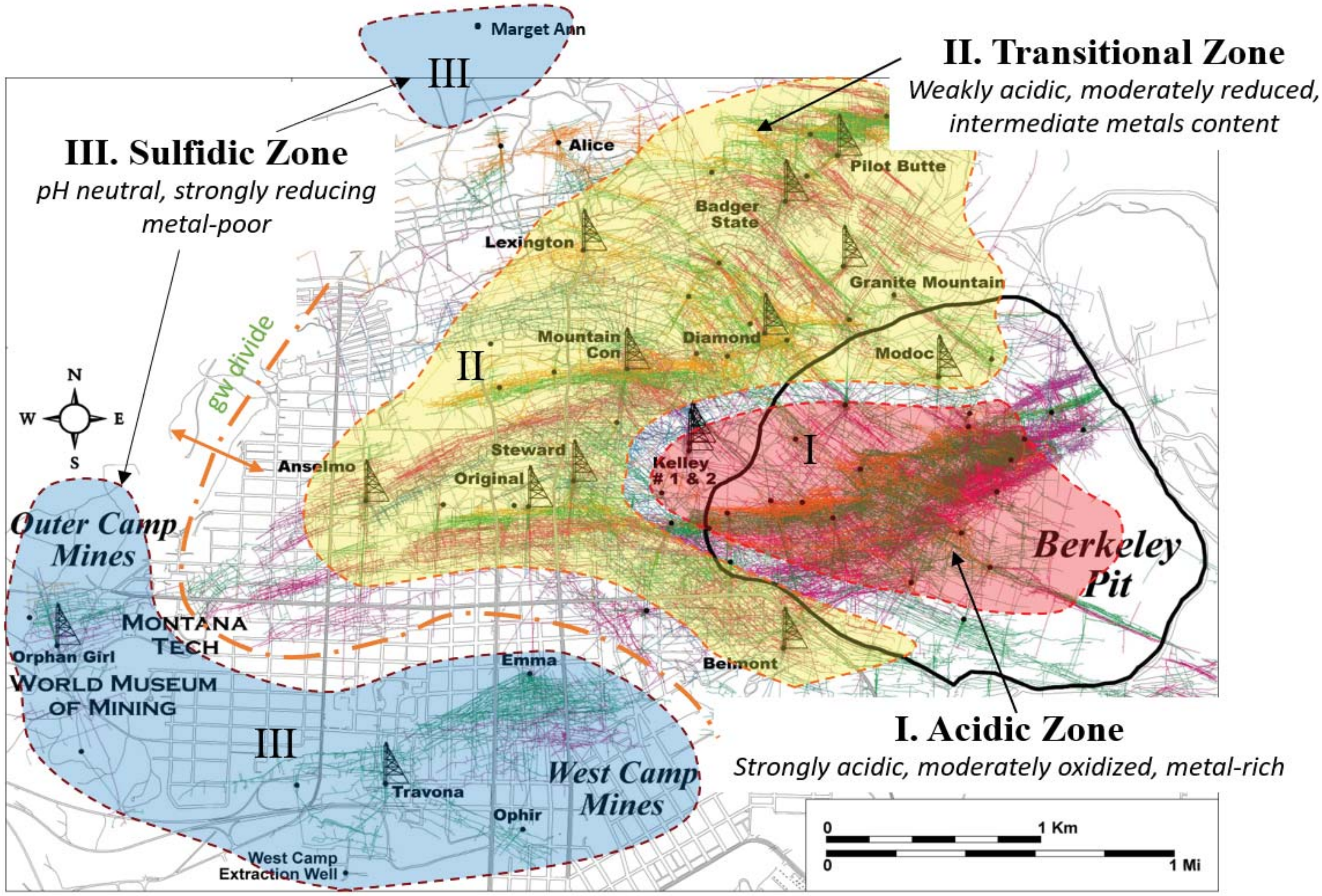

Figure 6. Map of the underground mine workings of Butte (modified from Duaime and others, 2004), showing district-wide zonation in mine water chemistry. The dashed blue line is a groundwater divide that separates the East Camp and West Camp mine pools. The boundary between the East Camp and Outer Camp is approximate.

Camp workings contain mine water with near-neutral pH, low metal concentrations, and a chemistry that is strongly reducing (H_2S-stable). The Orphan Boy/Orphan Girl shafts are particularly rich in H_2S (>10 mg/L), and S-isotopes verify that this H_2S formed by bacterial sulfate reduction (Roesler and others, 2007; Gammons and others, 2009). Decomposing timbers in the flooded mine workings (fig. 8A) are a possible source of organic carbon for fermenting microbes, which in turn supply the low molecular weight organic-carbon molecules needed for sulfate-reducing and other forms of anaerobic bacteria. The high concentrations of H_2S in the Orphan mine shafts have led to the growth of yellow greenockite (CdS) coatings on the walls of the underground mine at the 100 ft level (fig. 8B). These CdS coatings likely formed by reaction of H_2S gas with pore waters rich in Zn^{2+} and Cd^{2+} (Gammons, 2016).

The zonation in mine water chemistry at Butte is strongly influenced by the district-wide zonation in mineralogy of the veins and lodes of the mining district (Metesh, 2004; Gammons and others, 2009). The Cu-rich veins of the central zone have the highest pyrite content, with scarce amounts of acid-neutralizing minerals such as carbonates or fresh (unaltered) feldspars. Moving westward and northward from the center of the district, the veins have less pyrite, are richer in carbonate minerals (including rhodochrosite, calcite, dolomite), and the granite wallrock is less intensely altered. Thus, the general zonation in mine water chemistry from the central "acidic zone" to the "transitional zone," and thence to the "sulfidic zone" (fig. 6), approximately mimics the changes in ore deposit mineralogy from the center to the outer portions of the district.

Most of the flooded mine shafts of Butte contain water that is much warmer than background groundwater (table 3). Snyder (2008) found that the temperature and chemistry of water in each mine shaft shows almost no change with depth (up to 1000 feet below surface), implying some mechanism of vertical mixing. Gammons and others (2009) showed that the

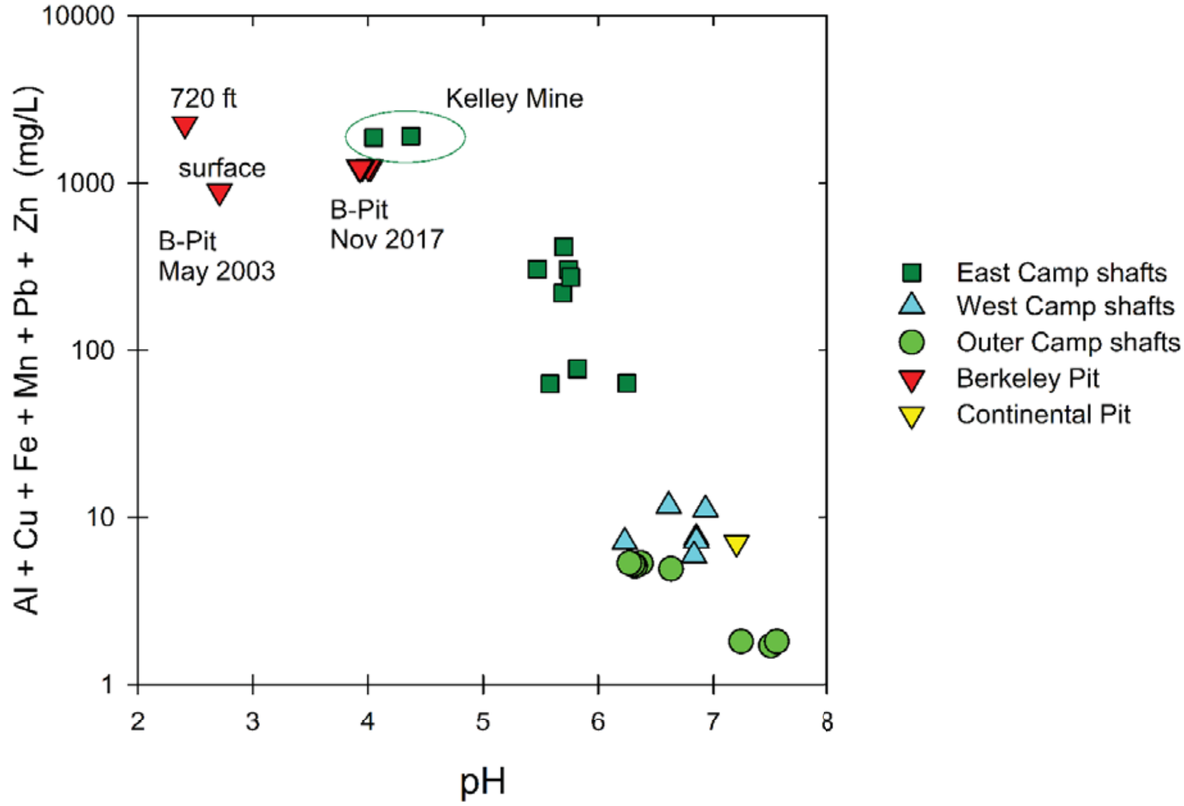

Figure 7. Sum of the concentrations of dissolved metals vs. pH for the flooded underground mines and the Continental Pit and Berkeley Pit lakes.

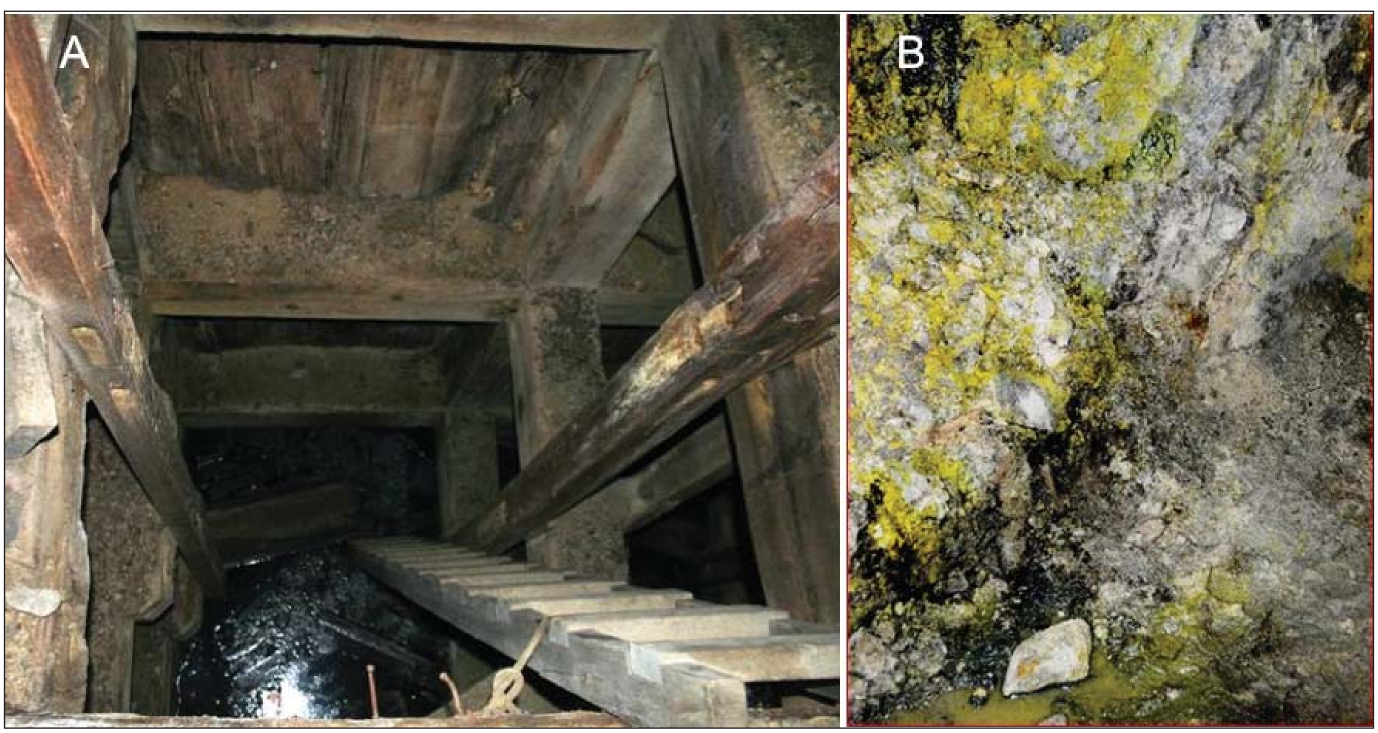

Figure 8. (A) View down the flooded Orphan Girl mine shaft. Water level is about 20 ft below the 100 ft access level. (B) Vivid yellow coatings of cadmium sulfide (greenockite) growing on the tunnel walls near the Orphan Girl mine shaft (field of view is 3 ft x 2 ft).

temperature of the water in each mine shaft in Butte is roughly equal to the average temperature between the top and bottom of the shaft based on the local geothermal gradient. Two mines plot off this trend with abnormally high temperature, the Kelley shaft and the Orphan Boy/Orphan Girl shafts. The reason for the abnormally warm waters in these mines is unclear, but regardless, the warm mine shaft waters represent a low-grade geothermal resource. A heat exchanger installed into the flooded Orphan Boy shaft is intermittently used to help heat and cool the newly constructed Natural Resources Building in which the MBMG is housed (Thornton and others, 2013).

One curious aspect of the flooded mine shaft water is the scarcity of dissolved copper. After all, the early underground workings at Butte were among the richest copper mines in the world. A possible explanation for the lack of dissolved copper (Gammons and others, 2009) is that it is precipitating out as chalcocite on the surface of other sulfide minerals in a manner similar to supergene enrichment. The supergene replacement of pyrite by chalcocite can be written as follows (from Zies and others, 1916):

$5FeS_2 + 14Cu^{2+}(aq) + 12H_2O \rightarrow 7Cu_2S$ (chalcocite) $+ 5Fe^{2+}(aq) + 3SO_4^{2-} + 24H^+$

Because copper has a much stronger affinity for sulfide than iron, the reaction is pushed strongly to the right, effectively scavenging all dissolved copper from solution. In contrast, in the more strongly oxidizing conditions of the Berkeley Pit, dissolved O_2 and/or dissolved Fe^{3+} destabilizes chalcocite, allowing dissolved Cu concentrations to reach high levels (>50 mg/L).

THE CONTINENTAL PIT AND THE ACTIVE MINING OPERATION

Because closure of the Berkeley open-pit mine resulted in a highly acidic and metal-rich pit lake, it is reasonable to wonder what might happen when the active Continental Pit is closed. The Continental mine is located roughly 2 km east of the Berkeley Pit. Despite this proximity, the geology of the two deposits is quite different in terms of a predisposition to generate acid and leach toxic metals. The Continental fault, a west-dipping normal fault with roughly 1 km of vertical displacement, separates the two ore bodies. Consequently, rock that is currently being mined is less intensely altered (e.g., fresh feldspar and biotite are present), has a lower pyrite content, and contains up to 1–2% calcite as veinlets and disseminations in the granite (Newbrough and Gammons, 2002). The Continental deposit also has a lower overall copper grade than the Berkeley, although the presence of <0.1% molybdenite helps to make the mine economic.

During the period 2000–2003, mining of the Continental deposit temporarily ceased due to unfavorable economics, and dewatering pumps were turned off. As a consequence, two small pit lakes began to form. The MBMG collected vertical profiles and samples from the north pit lake and found the water to be near-neutral in pH, well-oxygenated, with high bicarbonate alkalinity and relatively low trace metal concentrations (Duaime and Metesh, 2003b). Geochemical modeling by McGivern (2014) showed that the lake waters in 2003, as well as groundwater being pumped from the active mine, were near-equilibrium with calcite, dolomite, rhodochrosite, gypsum, brochantite ($CuSO_4 \cdot 3Cu(OH)_2$), malachite, hydrozincite ($Zn_5(CO_3)_2(OH)_6$), and powellite ($CaMoO_4$). Although some acidic springs are located around the perimeter of the Continental Pit, most of the rock being mined evidently has sufficient neutralizing potential to maintain a near-neutral pH. Whether this situation will persist into the future depends on the balance of acid-generating minerals (mainly pyrite) and acid-neutralizing minerals (calcite, plagioclase, and other silicate minerals) left on the mine walls after closure.

Approximately 2 km north of the Berkeley Pit, and almost 300 vertical meters higher, sits the YDTI (figs. 9, 10). About half of the impoundment consists of a "beach" of fine sand, with the other half containing finer sediment or "slimes" under a cover of water. The pH of the pond at the north end of the impoundment is strongly alkaline (pH 10 to 11) due to pH adjustments made in the concentrator plant. Owing to this high pH, the concentrations of most trace metals of concern are very low in the tailings pond (table 3). One exception is molybdenum, which has concentrations near 1 mg/L. More information on the hydrogeology and geochemistry of the tailings water can be found in Berzel (2017).

Figure 9. Aerial photograph of Butte showing the locations of important mining features.

Figure 10. Approximately 18,000 gallons per minute (1,130 L/sec) of mill tailings are discharged as a slurry (40% solids) into the Yankee Doodle impoundment (photo taken in October 2005).

ACKNOWLEDGMENTS

A large number of people have contributed indirectly to the writing of this paper, including (but not limited to): Larry Twidwell (Montana Tech), Dick Berg, Gary Icopini, James Madison, John Metesh, and Nick Tucci of the MBMG, and Montana Tech graduate students Jim Jonas, Jenna Kaplan, Amber McGivern, Damon Pellicori, Pam Reed, and Dean Snyder. We thank the US-EPA, BP-ARCO, Montana Resources, Montana NRDP, and Montana DEQ for past and current funding and support. Technical reviews were provided by Gary Icopini, Daryl Reed, and Nicolas Tucci.

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