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An investigation of acidic head-water streams in the Judith Mountains, Montana, USA

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ABSTRACT

Acid rock drainage exists in three headwater streams (Armells Creek, Collar Gulch, Chicago Gulch) in the Judith Mountains, central Montana, USA. The streams drain opposing sides of a central, pyrite rich, hydrothermally altered, granite-porphyry intrusion. Although significant production of precious metals has occurred elsewhere in the Judith Mountains, no present day mining is taking place and the drainages of interest have not been heavily impacted by historical mining activities. All three streams are acidic (pH < 4) in their headwaters and become pH-neutral with distance downstream due to the influx of alkaline groundwater and tributary flows. Concentrations of dissolved aluminum, cadmium, copper, lead, thallium, zinc and fluoride ion are locally well above regulatory standards. Detailed synoptic sampling using the continuous tracer injection method shows that metal loading is diffuse and is associated with weathering of the pyrite-rich bedrock, with negligible contributions of acid or metals from legacy mine waste. Each stream is precipitating hydrous ferric and aluminum oxides in discrete zones due to a combination of oxidation and acid-neutralization processes. An abundance of terraced ferricrete deposits shows that acid rock drainage existed prior to human disturbance. Furthermore, a comparison of the trace-metal content (Cu/Fe ratio) of modern, in-stream precipitates vs. ancient (undated) ferricrete deposits suggests that the chemistry of the streams has not changed significantly due to anthropogenic activity. The geochemistry of headwater streams in the Judith Mountains may provide a useful baseline comparison to nearby regions in central Montana with similar geology that have been heavily disturbed by historic and modern mining.

1. Introduction

Acid rock drainage (ARD) refers to the release of protons, dissolved sulfate, and associated metals and metalloids during weathering of pyrite and other sulfide minerals (Nordstrom, 1982a,b; Alpers et al., 1994; Nordstrom and Alpers, 1999). In most cases, ARD has been initiated or amplified by mining activities (Wireman and Stover, 2011). ARD is widely considered to be the most challenging environmental problem that the modern mining industry must face, and is also a major concern for other stakeholders, such as government agencies, land managers, and the general public. ARD has potentially serious effects on terrestrial and aquatic ecosystems which give rise to a host of multifaceted issues ranging from remediation and treatment strategies to human exposure and health concerns. These types of problems have long-term consequences and can be expensive to solve.

Although usually discussed within the context of modern or historical mining activities, ARD may also occur in streams that have had little or no human disturbance. Examples of natural ARD have been reported from Colorado, Montana, and New Mexico in the western USA (McKnight and Bencala, 1990; Furniss et al., 1999; Posey et al., 2000; Bird, 2003; Sjostrom et al., 2004; Verplanck et al., 2009). Some of these streams are in pristine, undisturbed settings (McKnight and Bencala, 1990; Bassett et al., 1992), whereas others have been influenced by mining but show evidence of pre-modern acidic drainage (e.g., Fernández-Remolar et al., 2003). In the latter case, it is often a challenge to determine pre-mining water-quality conditions (Runnells et al., 1992; Bird, 2003; Runkel et al., 2007). Many streams that experienced pre-modern ARD are characterized by the presence of ferricrete (Verplanck et al., 2007). Ferricrete typically consists of alluvial or colluvial gravel and cobbles cemented by a matrix of iron oxide or hydroxide (e.g., goethite, FeOOH). Ferricrete may crop out on the banks of streams as a ledge or terrace of erosionally-resistant material, often at some elevation above the modern streambed (Verplanck et al., 2009). Certain ferricrete deposits dated to

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>1000 y in age have been used as a record of climate change during the Holocene Epoch (Furniss et al., 1999; Sjostrom et al., 2004). Furthermore, Nimick et al. (2009) have shown that a comparison of the trace element concentration of fresh Fe-oxide precipitates forming in a stream vs. adjacent ferricrete deposits may be used to compare the water quality of acidic streams before and after human disturbance.

This study investigates the extent and origin of acidic drainage in three headwater streams (Armells Creek, Collar Gulch, and Chicago Gulch) in the Judith Mountains of central Montana, USA. Although there has been significant mining of precious metals elsewhere in the Judith Mountains (Weed and Pirsson, 1898; Robertson, 1950; Zhang and Spry, 1994; Woodward, 1995), historic mining has been minimal within the watersheds of this study. To augment routine water quality monitoring, additional field experiments were conducted in two of the streams (Armells Creek, Collar Gulch): (1) detailed synoptic sampling using the continuous tracer injection method (Kimball et al., 2002) to quantify longitudinal changes in metal concentrations and loads; (2) diel (24-h) sampling to examine short-term changes in the concentrations of trace metals (Gammons et al., 2005; Parker et al., 2007; Nimick et al., 2011); and (3) collection of a longitudinal transect of ancient ferricrete samples for trace metal analysis, to compare with modern HFO in-stream precipitates (Nimick et al., 2009).

2. Site description

The Judith Mountains are located near the geographic center of the State of Montana, USA, about 15 km to the northeast of the city of Lewistown (Fig. S1, Supplemental Files). The range forms an arc approximately 32 km long and 16 km wide and consists of a large number of late Cretaceous to early Tertiary plutons that have intruded into originally flat-lying Paleozoic and Mesozoic sedimentary rock (Wallace, 1953; Goddard, 1988; Porter and Wilde, 1993). The intrusions of the Judith Mountains belong to the Central Montana Alkalic Province (Marvin et al., 1980; Baker and Berg, 1991), which includes a number of other "island mountain ranges", including the Crazy Mountains, the North and South Moccasins, the Bears Paw Mountains, the Big Snowy Mountains, and the Little Rocky Mountains (Fig. S1, Supplemental Files). In all of these ranges, intrusions have caused uplift and doming of the surrounding sediments, contact metamorphism, and localized precious- and base-metal mineralization. Over time, due to natural weathering processes, the plutons have become exposed along the crest of the mountain ranges.

The geology of the immediate study area is dominated by porphyry intrusions of alkali granite, quartz monzonite, and syenite (Fig. 1, Goddard, 1988; Kohrt, 1991). Within these igneous rocks, centered on Judith Peak and Red Mountain (the two highest peaks in the central Judith Mountains at 1960 m and 1882 m, respectively), a prominent zone of hydrothermal alteration and pyrite mineralization exists. This alteration may reflect the presence of a buried porphyry Cu–Mo or carbonatite deposit (Hall, 1977; Lindsey and Fisher, 1985). In addition to pyrite, fluorite is widespread within the altered zone (Hall, 1977). All streams draining the zone of hydrothermal alteration on Judith Peak and Red Mountain are acidic in their headwaters, but become pH-neutral at lower elevation as the geology transitions into Paleozoic and Mesozoic sedimentary rock (Fig. 1). Both Armells Creek and Collar Gulch contain large, cliff-forming outcrops of the Mississippian Madison Limestone in their lower reaches. In

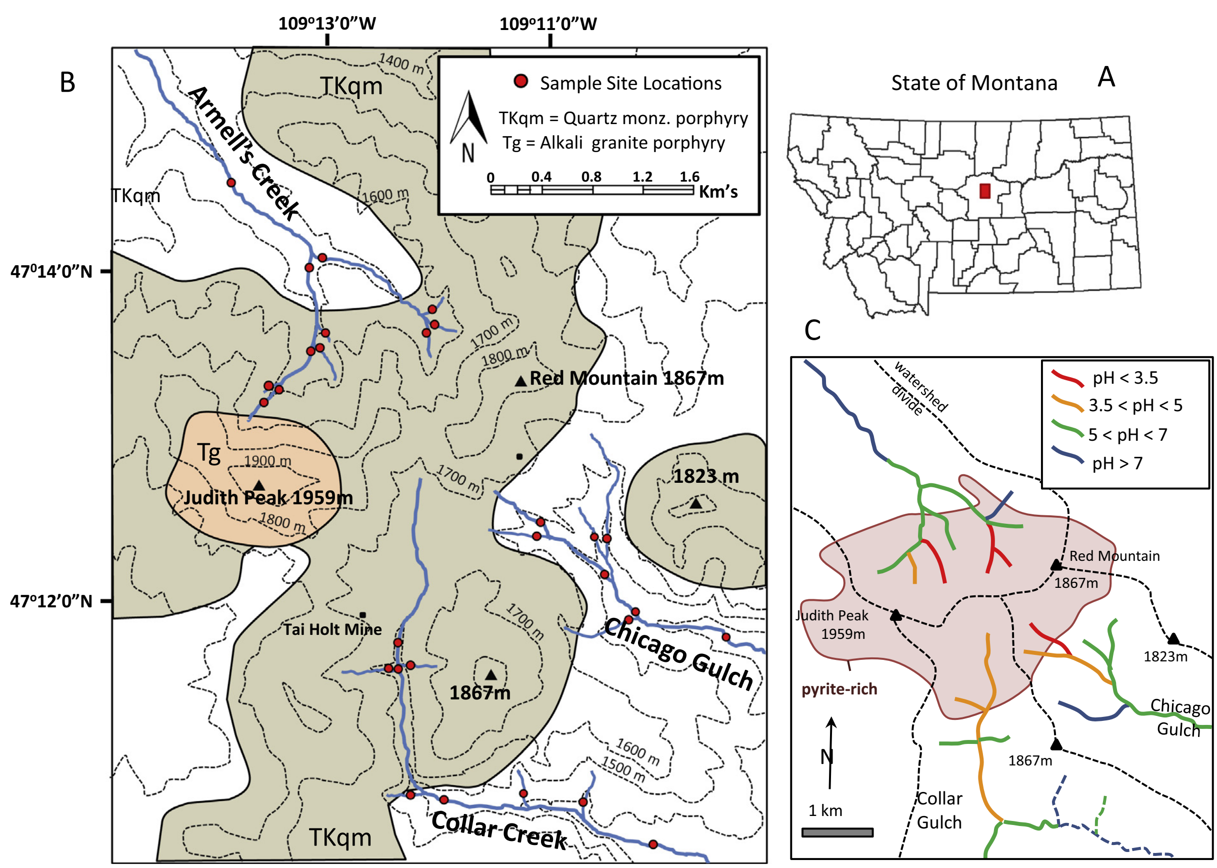

Fig. 1. Judith Mountains field area showing: (A) location within Montana; (B) sampling locations and geologic information; (C) the radial pattern of acid streams draining the central region of pyrite-rich alteration on Judith Peak and Red Mountain (C).