Mineralogical and geochemical behavior of mill tailing material produced from lead-zinc skarn mineralization, Hanover, Grant County, New Mexico, USA

Abstract
Mineral extraction and processing, especially metal mining, produces crushed and milled waste; such material, exposed to weathering, poses the potential threat of environmental contamination. In this study, mill tailings from inactive Pb–Zn mines in New Mexico, southwest USA, have been examined for their potential environmental impacts by means of detailed mineralogical and geochemical characterization. The principal ore minerals remaining in the tailings material are sphalerite, chalcopyrite, and very minor galena, smithsonite, and cerrusite, accompanied by the gangue minerals pyrite, pyrrhotite, magnetite, hematite, garnet, pyroxene, quartz, and calcite. White precipitate occurring on tailings surfaces is composed of gypsum and hydrated magnesium sulfates. Pyrite is mostly unaltered or shows only micron-scale rims of oxidation (goethite/hematite) in some surface samples. This iron oxide rim on pyrite is the only indication of weathering-derived minerals found by microscopy. There are variations in element concentrations with depth that reflect primary variations through time as the tailings ponds were filled. Cadmium and Zn concentrations increase with depth and Ag and Pb are low for the uppermost core samples, while Cu, Ni, and Co concentrations are generally high for the uppermost core samples. These elemental distributions indicate that little or no leaching has taken place since emplacement of the tailings because no accumulation or enrichment of these metals is observed in Hanover tailings, even in reducing portions of tailings piles. Element concentrations of surface samples surrounding the tailings reflect underlying mineralized zones rather than tailings-derived soil contamination. We observed no successive decreasing metal concentrations in prevalent wind directions away from the tailings. Stream sediment samples from Hanover Creek have somewhat elevated Zn, Cd, and Pb concentrations in areas that receive sediments from erosion of the tailings. However, input from tributaries downstream of the ponds appears to be principal source of heavy metals in Hanover Creek. The results of this study indicate that there is low risk for groundwater heavy-metal contamination from Hanover tailings. Tailings material do not show significant geochemical oxidation/alteration or metal leaching with depth. Our studies indicate that neutralizing minerals present in the tailings are sufficient to keep the tailings material chemically stable. Geochemically, however, tailings materials are being eroded and may pose a threat to Hanover Creek via siltation.

Key words: Mine waste · Metal leaching · Oxidation · Mill tailings

Introduction
Mineral extraction and processing, especially metal mining, produces crushed and milled waste; such material, exposed to weathering, poses a potential danger to the environment. Sulfide-bearing mineralization is notorious for having the potential for producing sulfuric acid through oxidation and leaching of heavy metal sulfides. Significant contamination of surface- and groundwater may result, and physical transportation of mill tailings may also pose health risks (Plumlee 1995; Alpers and others 1994). However, not all sulfide-containing waste materials present a threat to the environment, even though they contain geochemically significant heavy-metal contents. Through detailed mineralogical and geochemical studies it is possible to evaluate and quantify the environmental threat from mined materials; from this evaluation, geologically and economically reasonable remediation and reclamation recommendations may be made. Importantly,
such recommendations are based on mineralogic and thermodynamic assessment of the geochemical processes that are likely to occur or that are currently taking place within mined materials. In this study, mill tailings from several inactive Pb–Zn mines in the relatively arid New Mexico environment have been examined for environmental impacts (Fig. 1). Study of Pecos Mine tailings (northern New Mexico) indicate that the relative order of mobility is Cd > Zn > Cu > Pb; plants at the tailings site, growing in a naturally formed wetland at the tailings, have elevated heavy-metal concentrations (Sidle and others 1991; Chambers and Sidle 1991). Cleveland mine tailings (southwest New Mexico) are strongly oxidized in surface exposures (Walder and others 1994a; Adrian Brown Consultants 1991) and have a high material acidity (soil pH 2; Walder unpublished data). Waldo Mine tailings (central New Mexico) show stark orange–brown surface alteration, but apparently have no large-scale leaching and element movement with depth (Johnson 1987). Heavy-metals contamination of soil and surface water from abandoned and active mines are also reported from areas with greater precipitation and different soil types than New Mexico, such as Sardinia (Gregorio and Massoli-Novelli 1992), Wales (Fuge and others 1994), and Iron Mountain, California (Alpers and others 1994). These examples document the potential of failure of remediation efforts if geochemical considerations are not addressed during site assessment and reclamation.

Study area

Our study involves 3 km² of the Central Mining District, New Mexico, known for its numerous mineral deposits containing economically important Fe, Cu, Pb, Zn, Ag, and Au. This investigation was undertaken to describe and document the potential for groundwater, surface water, and colian-based contamination from mill tailings. Although mining has taken place in this area since the 1600s, volumetrically important tailings production began in the late 1800s when base- and precious-metal mining was undertaken in the Pinos Altos and Santa Rita areas (Lasky and Wootton 1932). This study involves mineralogic and geochemical assessments of Pb–Zn–Cu tailings materials, referred to here as the Hanover tailings, from the Empire Zinc Mine. We describe and document the mineralogical and geochemical characteristics of four smaller mill tailings ponds (about 100,000 metric tonnes) along Hanover Creek and one larger tailings pond (about 6,000,000 metric tonnes) (Walder 1993a) east of the Bull Hill area near Hanover, Grant County, New Mexico (Fig. 1). The Hanover mill tailings cover an area of approximately 0.22 km². We also examined the tailings material distributed by alluvial and eolian processes into adjacent soils, and tailings now incorporated into Hanover Creek stream sediments.

The ore from which the mill tailings have been produced is a massive sphalerite replacement deposit in limestone (skarn deposit) related to the Hanover–Fierro stock (Jones and Hernon 1973). Sphalerite was the principal ore mineral, occurring with volumetrically minor chalcopyrite and galena; trace element analyses show that Hanover sphalerite contains variable quantities of Mn, Pb, and Cd (Jones and Hernon 1973; Schmitt 1939). Andradite garnet is the most abundant silicate mineral replacing limestone, with pyroxene (hedenbergite to ferrosilite), ankerite, specular hematite, pyrite, pyrhotite, and calcite present in variable quantities as gangue minerals.

Froth flotation was the main recovery method utilized during most ore processing at the Empire Zinc Mine. Notably, this process uses lime to suppress and, therefore, separate pyrite from the other ore sulfide minerals during flotation. Flotation methods replaced gravity separation techniques, used for a short time during the early stages of mining. Because gravity separation was applied to the high-grade ores mined during initial mine production, and because such separation requires less crushing than that needed for froth flotation, tailings from the early mining period are substantially coarser than those generated during later processing.

Rocks surrounding and underlying the Hanover tailings are mainly Magdalena Group limestones (Syrena Formation, Oswaldo Formation). These Pennsylvanian limestones are intruded by late Cretaceous to early Tertiary quartz diorite porphyry dikes and hornblende quartz diorite sills (Jones and others 1967). Lake Valley Limestone of Lower Mississippian age is present on the northern side of the Hanover–Fierro granodiorite porphyry (Jones and others 1967).

The main emphasis of this study has been to determine concentrations of the elements Pb, Cd, Se, As, Ag, Hg, and Be in the tailings materials; assess their mobility within the tailings; and evaluate the potential risk for groundwater contamination. In addition to these constituents, the mineralogic setting of the highly soluble elements Zn and Cu and the weakly soluble elements Ni, Co, and Bi have been ascertained. Mineralogical investigations using standard ore microscopy studies of polished heavy-mineral sepa-