



## ***Closure and reclamation of the Hanover-Empire zinc mine area, Grant County, New Mexico***

Robert W. Newcomer, Douglas E. Romig, and Walter Niccoli  
2008, pp. 151-157. <https://doi.org/10.56577/FFC-59.151>

in:

*Geology of the Gila Wilderness-Silver City area*, Mack, Greg, Witcher, James, Lueth, Virgil W.; [eds.], New Mexico Geological Society 59<sup>th</sup> Annual Fall Field Conference Guidebook, 210 p. <https://doi.org/10.56577/FFC-59>

---

*This is one of many related papers that were included in the 2008 NMGS Fall Field Conference Guidebook.*

---

### **Annual NMGS Fall Field Conference Guidebooks**

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

### **Free Downloads**

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

### **Copyright Information**

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

*This page is intentionally left blank to maintain order of facing pages.*

## CLOSURE AND RECLAMATION OF THE HANOVER-EMPIRE ZINC MINE AREA GRANT COUNTY, NEW MEXICO

ROBERT W. NEWCOMER<sup>1</sup>, DOUGLAS E. ROMIG<sup>1</sup>, AND WALTER NICCOLI<sup>2</sup>

<sup>1</sup>Golder Associates Inc., 5200-C Pasadena NE, Albuquerque, NM 87113, [rnewcomer@golder.com](mailto:rnewcomer@golder.com)

<sup>2</sup>Cobre Mining Company, P.O. Box 7, Hurley, NM 88043

**ABSTRACT** — The closure and reclamation of the Hanover-Empire Zinc mine area was designed to take advantage of the large volumes of alkaline waste rock available at the site. Waste rock piles at the site were mapped and classified based largely on their sulfide and carbonate contents using standard geological field procedures and acid-base accounting analytical methods. Additionally, representative waste rock samples were collected and analyzed to evaluate their suitability as a cover material capable of supporting revegetation. Results of the investigation were used to develop a conceptual closure plan for the features at the site. The components of closure ultimately included the dewatering of two large pits, structure demolition and scrap disposal, stockpile removal to pits and quarries, regrading and covering of reactive materials with alkaline waste rock, construction of surface water controls along Buckhorn Gulch, highwall fencing, safeguarding shaft and adits and seeding and revegetation.

### INTRODUCTION

The principal reclamation challenges associated with the Hanover-Empire Zinc (Hanover) mine area involved the characterization of the different types of waste rock, control of surface water, backfilling of mine voids and highwalls to reduce public hazards, stabilization of the waste rock piles to prevent off-site dispersal and the establishment of sustainable vegetation on the top surfaces. The Hanover mine area is south of Cobre Mining Company's (Cobre) Continental mine approximately 23 km east-northeast of Silver City in Grant County, New Mexico (Fig. 1). The Hanover mine is in the Central Mining District and includes workings in Buckhorn Gulch and the waste rock piles, zinc pits, and associated features within a total disturbed area of approximately 150 acres.

### MINING HISTORY

Zinc ore was produced from the Hanover mine area beginning in the early 1900s from massive sphalerite replacement deposits around the Hanover-Fierro stock. The mine workings in the Hanover area are shown on Figure 1. Some of the zinc grades associated with the replacement ores have been described as being approximately 14%, along with 1 to 2% Cu, 0.1% Pb, and up to 1.3 oz/st of Ag (Hernon and Jones, 1970). Empire Zinc began mining and zinc production in about 1902 (Hernon and Jones, 1970). Production from the mines in the Hanover mine area was reported at 3,583,961 st, averaging 8.67% Zn and 0.21% Pb between 1902 and the mid 1980s (Hart, unpubl. 1985). A summary of the production history was compiled for the Continental mine area (located immediately north of the Hanover mine area and is presented in Golder, unpubl. 2005). The most recent production from the Hanover mine area occurred sporadically for a cumulative period of approximately 17 months between January 1, 1970 and June 18, 1993. The mines were inactive after that time, although the Hanover no. 8 shaft is currently retained as a water supply source. In the past, during operation of the mill at the Continental mine, water was pumped by Cobre from the Hanover no. 8 shaft (Cobre, unpubl. 1996).

### GEOLOGY AND ORE DEPOSITS

The geology of the Continental mine area, which includes the Hanover mine area, has been described in Hillesland et al. (1995) and Jones et al. (1967). Much of the information was developed from surface and subsurface mapping, exploratory drilling, and historical mining record. The Hanover and Continental mine areas, according to Hillesland et al. (1995), consist principally of ore deposits formed in sedimentary and metasedimentary rocks that were intruded by a variety of igneous rocks. The zinc ore in the Hanover mine area was associated with the metasedimentary rocks formed adjacent to the Hanover-Fierro stock. The stock intruded the sedimentary section and is the largest of a series of plutons in the area; it is somewhat oval in plan view, and extends approximately 4 km in a north-south direction. The stock is surrounded by an igneous metamorphic aureole, chiefly manifested by replacement skarns in the carbonate rocks and shales. At the southern end of the stock, the younger Paleozoic carbonate rocks have higher calcium contents than the older, more magnesium-rich Paleozoic carbonate rocks in contact with the stock at the northern end. This has resulted in distinctive mineralogy of the various skarns in the two areas. Skarns in the limestones in the Hanover mine area typically contain calcic minerals, garnet, epidote, hedenbergite, tremolite, ilvaite, as well as sphalerite and pyrite. Skarns in the older carbonates in the Continental mine area are more magnesian rich. The mineralogies tend to be zoned both locally within the individual ore zones as well as regionally.

According to Park and MacDiarmid (1975), the mineral deposits in the Hanover mine area occur primarily in skarns in the upper Paleozoic carbonate rocks along the contact with the intrusive Hanover-Fierro stock. Mineralization is concentrated in these contact zones along various structural-control features. The ore-bearing hydrothermal fluids ascended most readily along the higher permeability zones associated with fractures and the more permeable skarn zones. Much of the ore in the Hanover mine area is concentrated in the skarn formed in the Mississippian Lake Valley Limestone immediately below a parting shale, a lower unit of the overlying Pennsylvanian Oswaldo Formation. The skarn in the Lake Valley Limestone largely controlled the deposition

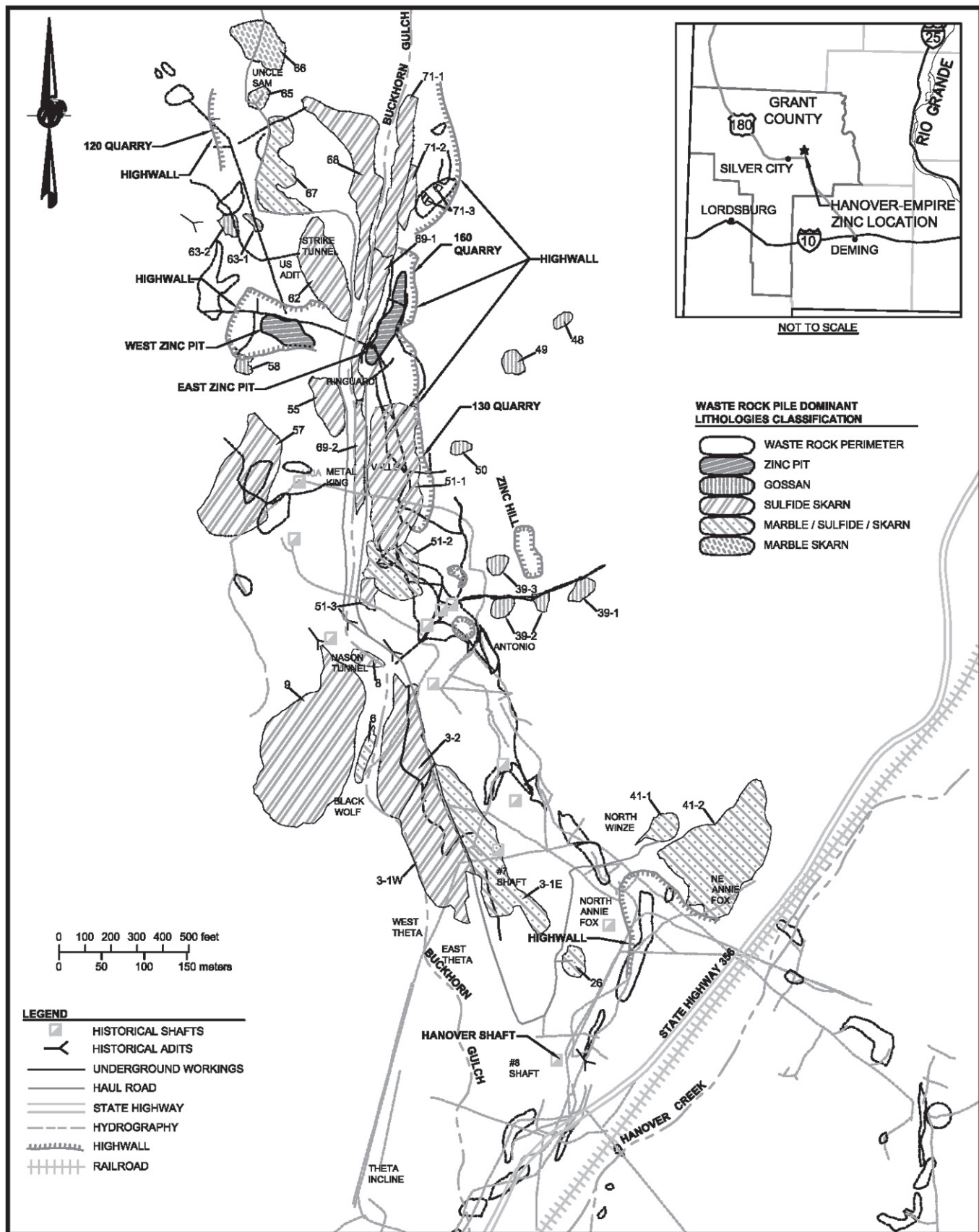


FIGURE 1. The Hanover and Empire Zinc mine area along Buckhorn Gulch showing locations of the principal mine openings, quarries and waste rock piles.

of the sulfide ore minerals in the metamorphic aureole near the stock.

Babcock (1953) noted in the Hanover mine area that the proportion of silicate minerals to ore minerals generally decreases from east to west away from the sedimentary rock contacts with the Hanover-Fierro stock and is also reflected by the silicate to marble ratio. Therefore, waste rock on the west side of Buckhorn Gulch tended to have a higher carbonate content than waste rock from the east side.

Leached outcrop and distinctive gossan are present in the rocks in the Hanover area that were above the sulfide-rich mineralized zones and the paleo water table surfaces. In some of these areas remnants of gossan are still present. The gossan zones were typically stripped during surface mining operations to get access to the deeper sulfidic zones.

### WASTE ROCK CHARACTERIZATION AND CLASSIFICATION

Prior to developing the closure and reclamation plans for the site, the area was investigated to evaluate the material characteristics of the various waste rock piles. The investigation included mapping and sampling of waste rock with specific attention on the suitability of the carbonate-bearing waste rock as potential cover and backfill material for the two zinc pits and other open cuts and quarries. The term quarry has been used to describe areas where large underground stopes reached the surface.

The composition of each waste rock pile was evaluated by traversing the piles and mapping and describing the lithologies and estimating the percentages of rock types. Additionally, trenching was done on the top surfaces to evaluate their character and composition at depth. Estimates of the volume percentage of the different rock types were noted for each waste rock pile. Larger piles were subdivided if certain areas had significantly different characteristics and were evaluated separately.

The waste rock piles or portions of piles were mapped and classified based on their dominant lithologies as follows: marble/skarn dominated; mixed marble/sulfide/skarn; sulfide/skarn dominated; and gossan (Fig. 1; Table 1). This classification scheme was developed in part to assess the potential reactivity (acid generation) and suitability as a neutral cover material based on the percentage of sulfide and carbonate minerals. The marble/skarn dominated and mixed marble/sulfide/skarn waste rock classes were those materials with large proportions of carbonate with minor sulfide. Waste rock piles with a mixture of marble/sulfide/skarn waste rock were either 1) more heterogeneous mixtures of marble, sulfide, and epidotized skarn (for example, waste rock piles 65, 66 and 67 located on the northern and eastern sides of the "120" quarry); or 2) moderately well segregated marble/skarn and sulfide/skarn materials (for example, waste rock pile 68, which came from the Uncle Sam Tunnel) (Fig. 1).

The other waste rock piles contained less heterogeneous mixtures of marble/sulfide/skarn waste rock and included piles 6, 8, 9, 26, 62, 3-1 (East), 41-2, and 63-1 (Fig. 1). Waste Rock Pile 6 running parallel to the drainage had high carbonate content and came from the Nason Tunnel. Waste Rock Pile 8 is small and

came from a nearby adit. Waste Rock Pile 9 was one of the largest piles in the area and the source was the 130 and 160 quarry operations. The material content was variable, with a locally high pyrite and moderate carbonate content. Waste Rock Pile 26 was a small remnant of a much larger pile that was pushed down the hill as part of a prior reclamation effort conducted on the Annie Fox Pit. The carbonate content of this material was high. Waste Rock Pile 62 was a mixed pile that came from the Strike Tunnel and "120" quarry. This pile had some sulfides along with a large amount of marble. Material from Waste Rock Pile 3-1 East came from underground workings of the No. 7 Shaft.

Waste rock piles dominated by sulfide/skarn material included 55, 57, 68, 3-1 (West), 3-2, 51-1, 51-2, 69-1, 69-2, 70-1, and 71-2 (Fig. 1). In these piles, the marble/carbonate and skarn components were less than 25%. The waste rock in these piles was generally highly-altered reddish-orange to brown with secondary iron oxides, which included ferrihydrite, hematite, and limonite. Primary sulfides identified in these piles included pyrite, with some sphalerite, and rare chalcopyrite and galena. These sulfide-rich waste rock piles were identified by the abundance of medium- to coarse-grained, subhedral to euhedral to blebby sulfides. Waste Rock Piles 55 and 57 came from the "120" quarry. Waste Rock Pile 68 came from the Uncle Sam Tunnel and had a higher marble content in places, but some of the pile along the gulch was high in sulfides and low in carbonates. The waste rock piles 3-1 (West) and 3-2 came from underground workings of the No. 7 Shaft. Waste rock pile 51-1 was scattered along benches on the west side of the "130" quarry and contained material high in sulfides and low in carbonate. Waste Rock Pile 51-2 came from the stripping of the uppermost benches of the "130" quarry. Waste Rock Piles 69-1, 71-1, and 71-2 are similar to 51-2 with respect to sulfide mineralization and relatively low carbonate content.

The gossan waste rock piles included 48, 50, 58, 39-1, 39-2, and 63-2 (Fig. 1). Iron gossan waste rock piles were easily identified by color and the abundance of black, stringy iron and manganese oxyhydroxides and massive primary magnetite. These waste rock piles are a unique reddish-brown color as a result of oxidation of primary magnetite to secondary iron oxide phases, includ-

TABLE 1. Waste rock pile classification.

Waste Rock Pile	Classification (Predominant Waste Rock Composition of Pile)
65, 66	Marble/skarn
3-1 West, 3-1 East, 3-2, 6, 9, 26, 41-1, 41-2, 63-1, 67, 68	Mixed marble/sulfide/skarn
8, 9, 51-1, 51-2, 51-3, 55, 57, 62, 68, 69-1, 69-2, 71-1, 71-2	Sulfide/skarn
39-1, 39-2, 39-3, 48, 50, 58, 63-2	Gossan



ing hematite and limonite/ferrihydrite. Waste Rock Piles 48 and 50 are located on the crest of Zinc Hill. They have a high garnet content and are low in carbonate material. Waste Rock Pile 63-2 is a small pile consisting mostly of gossan. The mine workings that were the source of Waste Rock Piles 39-1, 39-2, and 39-3 extended beyond the oxide zone and reached sulfide mineralization at depths of approximately 25 to 30 feet; therefore, minor pyrite was observed in some of these materials.

### Waste rock chemical characteristics

Acid-base accounting (ABA), saturated paste pH and electrical conductivity (EC), and metal extraction tests were used as tools to identify potentially reactive materials and contaminants that could be mobilized from the waste rock. ABA and saturated paste pH and EC are relatively rapid and inexpensive screening tools used in evaluating and categorizing the relative acid-forming potential and acid-neutralizing potential of a waste rock and the suitability of materials as vegetative substrate. Representative samples from each of the waste rock piles were collected and submitted for analyses to Energy Laboratories in Billings, Montana.

At the lab, the samples were initially passed through a #10 mesh for pH, EC and extract analyses. For ABA, a sub-sample was pulverized to pass a #100 mesh for the sulfur speciation and neutralizing potential analyses (Golder, unpubl. 2005). ABA analytical methods are routinely applied to the analysis of mine waste materials to assess the potential for the materials to generate acid upon weathering (Jennings and Dollhopf, 1995) and also to estimate the amount of alkalinity or acid neutralizing potential available (Sobek et al., 1978).

### Saturated paste pH

Only two of the 55 waste rock samples had saturated paste pH values less than 5.5, which is a value used to evaluate the relative suitability of materials for revegetation (Golder, unpubl. 2005). The samples were from piles 57 (strongly altered sulfide) and 39-1 (gossan) and both had paste pH values of 5.4. Most of the samples were alkaline to slightly acidic with values ranging from 5.8 to 8.2. Piles consisting predominantly of marble/skarn had an average saturated paste pH value of 7.4. The saturated paste pH of the marble/sulfide/skarn waste rock piles ranged from 6.7 to 8.0 (average 7.3). Sulfide/skarn and gossan typically had lower saturated paste pH values, ranging from 5.4 to 8.2 (average 6.3) and 5.4 to 6.9 (average 5.9), respectively.

### Sulfur concentrations and speciation

Total sulfur concentrations and the sulfur species present in the waste rock also provide an indication of the acid generating potential (AP) of the samples (Sobek et al., 1978). The AP is characterized as the potential acidity based on an analysis of total sulfur and pyritic sulfur and assuming the acidity was derived largely from the oxidation of pyritic sulfur. Total sulfur concentrations ranged from 0.3 to 1.8% in marble/skarn samples, 0.1 to 5.0% in mixed

marble/sulfide/skarn samples, 0.06 to 9.0% in sulfide samples, and 0.05 to 0.6% in gossan samples. In general, total sulfur was not well represented by the sulfide concentrations. The deficiency was accounted for by the sulfate sulfur and "residual" sulfur concentrations. The concentration of residual sulfur was highest in sulfide/skarn samples, with a concentration range of 0.02 to 8.2% (average 0.7%). In general, samples that had high residual sulfur concentrations contained elevated levels of total sulfur and low neutralization potentials (NPs). Samples of marble/skarn and marble/sulfide/skarn had low concentrations of sulfur, and were dominated by the soluble or extractable fraction that is attributable to sulfate. Sulfide/skarn samples, which typically contained higher total sulfur concentrations, had higher concentrations of hot water extractable sulfate sulfur and HCl extractable sulfur. The average concentrations of hot water and HCl extractable sulfur in sulfide/skarn samples was 0.15 and 0.04%, respectively. Gossan samples typically had negligible sulfur concentrations.

### Neutralization potentials

Determination of the neutralization potential (NP) typically involve the reaction of the sample with a mineral acid of measured quantity, determination of the base equivalency of the acid consumed and conversion of the measured quantities to a NP in units of tons of calcium carbonate per kiloton ( $t \text{ CaCO}_3/\text{kt}$ ). The sample NPs were highest in marble/skarn and marble/sulfide/skarn samples, with average concentrations of 490 and 303  $t \text{ CaCO}_3/\text{kt}$ , respectively. The average NPs of sulfide/skarn and gossan samples were 95 and 18  $t \text{ CaCO}_3/\text{kt}$ , respectively. The wide range in NPs was thought to be a function of the variable carbonate content of the waste rock.

A number of criteria have been proposed for assigning acid rock drainage (ARD) potential to a material using ABA results (Price, 1997). The criteria proposed by Price (1997) are shown in Table 2. The most common approaches are those based on use of the neutralization potential ratio ( $\text{NPR} = \text{NP}/\text{acid potential [AP]}$ ) and the net neutralization potential ( $\text{NNP} = \text{NP} - \text{AP}$ ). For the purpose of this study, AP was calculated using sulfide-sulfur. Sulfide-sulfur was used to represent "reactive" sulfur. Bulk NP was used in calculations of NNP and NPR. For several reasons, no single ratio or NNP value has been identified to have universal applicability in terms of predicting acid generation. The actual threshold values for a particular solid are material-specific and depend on many factors, including the amounts and types of acid generating and neutralizing minerals, morphology, grain size, crystallinity, chemical composition, paragenesis, texture, and the site-specific exposure conditions.

Of the all the waste rock samples analyzed, and for which an NPR was calculated, only 9% had a NPR less than 1; 19% were between 1 and 2, 17% between 2 and 4, and 55% were greater than 4. There also appeared to be no apparent correlation between NPR and saturated paste pH. Sulfide/skarn and gossan waste rock samples had the lowest average NPR values, of 6 and 5, respectively. Only 9% of all samples have NNP values of less than 0  $t \text{ CaCO}_3/\text{kt}$ . Negative values of NNP indicate a potential to generate acidic drainage, whereas positive NNP indicates a propensity

TABLE 2. The general neutralization potential ratio (NPR) criteria from Price (1997) and definitions of acid-base accounting (ABA) terms used in the text.

Potential to generate ARD	Criteria	Comments
Likely	$\text{NPR} < 1$	Likely acid generating, unless sulfide minerals are non-reactive.
Possible (uncertain)	$1 < \text{NPR} < 2$	Possibly acid generating if NP is insufficiently reactive or is depleted at a rate faster than sulfides.
Low	$2 < \text{NPR} < 4$	Not potentially acid generating unless significant preferential exposure of sulfides along fractures planes, or extremely reactive sulfides in combination with insufficiently reactive NP.
None	$\text{NPR} > 4$	

## Explanation:

ABA – Acid-base account, which is calculated by various methods, but generally reflects the net of the acid neutralizing potential less the acid generating potential of a sample. Positive values reflect a net acid neutralizing and negative values a net acid generating potential.

ARD – Acid rock drainage.

NP – neutralization potential, which is the amount of neutralizing bases, including carbonates and is found by treating a sample with a known excess of standardized hydrochloric acid. The calcium carbonate equivalent of the sample is obtained by determining the amount of unconsumed acid by titration with standardized sodium hydroxide.

AP – acid potential, which is calculated using the sulfide-sulfur, or nitric acid extractable sulfur content of the sample.

NNP (net neutralization potential) = NP – AP.

NPR (neutralization potential ratio) = NP/AP.

for neutralization of acidic drainage. The samples analyzed that had a negative NNP also had NPR values of less than 1.

### Trace Metal Extractions

Extractions of leachate from waste rock samples were analyzed to evaluate the potential mobility of selected metals and other constituents (Golder, unpubl. 2005). For the few samples with saturated paste pH values less than 6, a saturated paste extraction was analyzed for the acid-soluble constituents of concern (i.e., aluminum, sulfate and fluoride). In this case, the extractant was deionized water, which was expected to have a leaching effect similar to rain water. Metals of concern, along with sulfate and fluoride, samples were expected to be more soluble in the acidic samples. The samples with saturated paste pH values greater than 6 (alkaline samples) were subjected to extraction using the ammonium bicarbonate-diethylenetriaminepentacetic acid (AB-DTPA) extraction method and selected metals were analyzed (American Society of Agronomy, 1982). The AB-DTPA extraction method was originally developed as a crop deficiency test to determine the concentration of essential trace elements. Thus, AB-DTPA extractant is considered more aggressive than water and the method generally yields higher concentrations of elements than comparable water extractions. While the AD-DTPA extraction is commonly used to assess the bioavailability of trace metals in soils it has not been shown to correlate with potential plant toxicity or metal mobilization. The concentrations of metals in both extracts were determined by either inductively coupled plasma (ICP) or ICP/mass spectrometry methods (Golder, unpubl. 2005).

The saturated paste and AB-DTPA extracts from all 58 samples were analyzed for arsenic, cadmium, copper, lead, manga-

nese, and nickel. The AB-DTPA extracts were also analyzed for molybdenum. The saturated paste extracts from the six samples that had paste pH values less than 6 were analyzed for aluminum, chromium, cobalt, iron, zinc, fluoride and sulfate. Most metal and the fluoride concentrations were less than or near the analytical reporting limit in samples with saturated paste pH values less than 6. Zinc concentrations in the saturated paste extracts ranged from 0.85 to 77 milligrams per kilogram (mg/kg). Cadmium concentrations in the extract ranged from less than detection to 0.21 mg/kg and copper from less than detection to 1.23 mg/kg. Sulfate concentration in the six samples ranged from 34 to 607 mg/kg.

The highest metal concentrations in AB-DPTA extracts from the alkaline samples were copper and lead. Copper ranged from 12 to 314 mg/kg and lead from less than detection to 66.7 mg/kg. Manganese concentrations ranged from less than detection to 47.6 mg/kg and cadmium from 0.1 to 11.2 mg/kg.

### CLOSURE AND RECLAMATION

The principal objectives for closure and reclamation of the Hanover mine area were to segregate and cover potentially reactive waste rock, dewater the two zinc pits, safeguard mine openings, regrade and cover waste rock materials and other disturbances, construct surface water control structures and reseed-ing. Carbonate-bearing waste rock was identified as a potential borrow source for cover and backfill early in the project because of the limited availability of more conventional borrows sources, such as soils. Examples of the dramatic changes to the landscape resulting from the reclamation project are illustrated in Figure 2. Reclamation included placement of a predominantly non-acid generating top dressing over the more reactive materials to



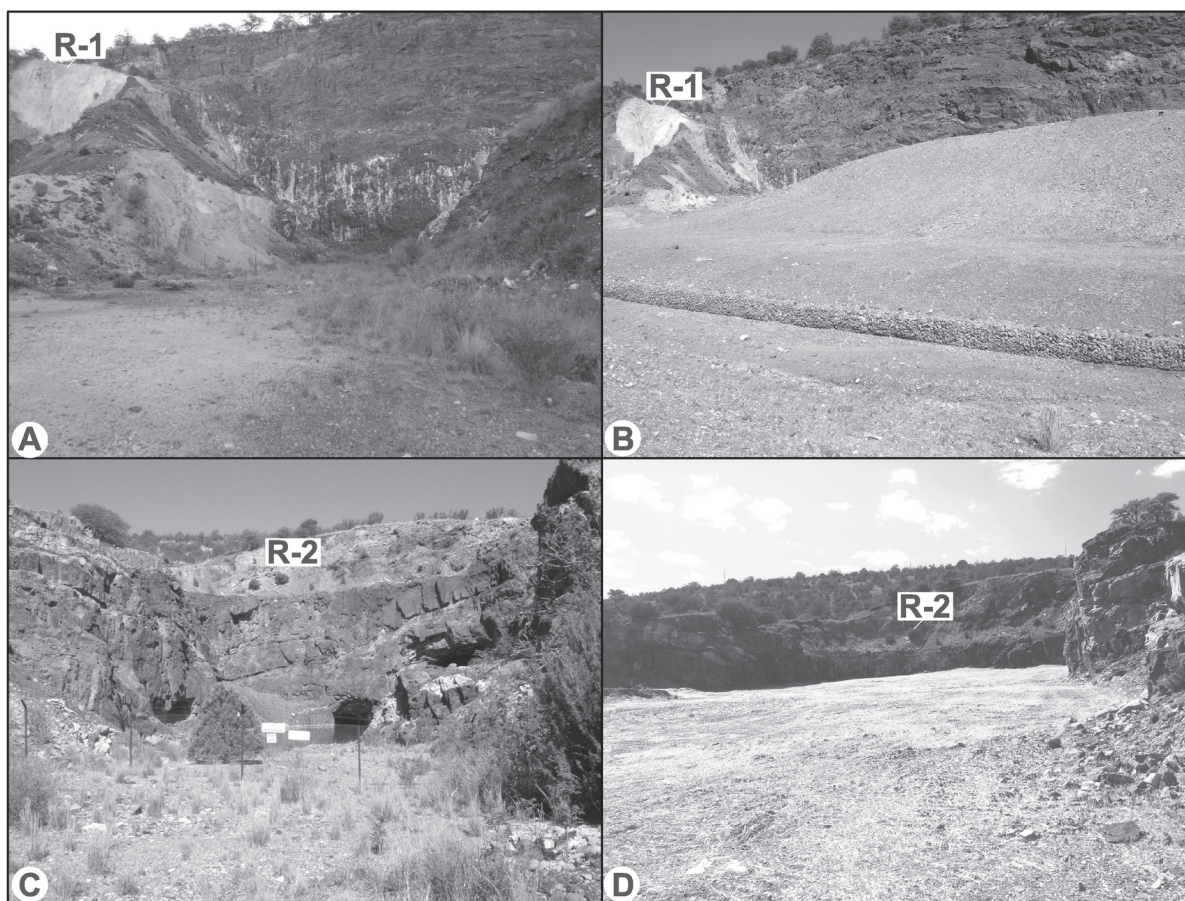


FIGURE 2. Selected views disturbed areas in the Hanover and Empire Zinc mine area before and after reclamation. **A**, View of the south end of the east zinc pit before reclamation, note reference point R-1. **B**, View of the south end of the east pit after reclamation of waste rock pile and partial backfill against the highwall. **C**, View of east zinc pit, note reference point R-2. **D**, View of east zinc pit following backfilling of pit.

establish vegetation, construction of wildlife enhancements, particularly bat grates in adits and shafts, and installation of fencing around physical hazards.

The two zinc pits contained approximately 7.1 million gallons of water, which was pumped to the Continental mine prior to backfilling (Telesto Solutions, unpubl. 2007). Fifteen waste rock piles that comprised about 134,000 cubic yards (cy) were completely removed and placed as fill in the pits and quarries. Four waste rock piles were regraded in place and covered with suitable waste rock. About 148,000 cy were excavated from nine waste rock piles and used as cover or placed as fill in the pits and quarries. Two carbonate-rich waste rock piles were regraded in place with no cover. The waste rock piles left in place and/or partially removed were regraded to a maximum slope of 2.5:1 (horizontal to vertical) or to match the natural topography if steeper (Telesto Solutions, unpubl. 2007).

#### Material Handling

A material handling plan was developed to use on-site waste rock materials in a manner to minimize environmental impacts and create a stable surface capable of supporting vegetation. Piles

with potentially reactive waste rock (skarn/sulfide or gossan) were excavated first and used as substratum to backfill pits and highwall areas. These locations are expected to have geochemical environments that would slow or suppress oxidation processes. Specifically, reactive materials were placed below the projected groundwater table in the former zinc pits to reduce the oxidation of sulfides or were covered to limit their contact with infiltrating water.

Non-reactive waste rock materials containing carbonate material were used as cover to provide a suitable substrate to support plants and minimize potential impacts to surface water. Evidence that these materials were suitable as a cover materials were the well-established native grasses, forbs, shrubs, and trees that had been recruited from the adjacent undisturbed areas. The performance of volunteer vegetation appeared to be independent of waste rock chemistry and more affected by either compaction or the lack of fines (materials with 90% or more rock by volume). Thus, the suitability of cover materials was a function of both carbonate mineralogy and a fine earth fraction of greater than 30%. Moreover, the non-reactive waste rock was preferred cover material because it does not involve additional disturbance to develop borrow materials.



Site grading and backfilling were designed to achieve positive drainage away from the highwalls; cover mineralized portions of the highwalls; provide for efficient water conveyance; limit slope length and gradient for erosional stability; and minimize future maintenance requirements. Grading was also necessary to blend reclaimed areas in with the natural topography.

### Revegetation

Revegetation was achieved by seeding the site with a seed mixture of native perennial grasses, shrubs, and forbs to promote erosional stability and provide wildlife habitat. All disturbed areas were ripped to approximately 12 inches along the contour to break up compaction, roughen the surface, and prepare the seedbed. The roughened surface also provided micro-sites for seedling establishment and reduced concentrated overland flow and erosion during the initial plant establishment period. The site was seeded with a rangeland drill and then mulched with straw at a rate of 2 tons per acre.

### Closure of Mine Openings

In general, the mine openings in the Hanover mine area were safeguarded by backfilling with mechanized equipment. In most cases, the mine opening and void closures involved simple backfilling with waste rock materials available on site. Fill was also placed against highwalls above the visible evidence of seepage, which was usually manifested as a zone of precipitated sulfate salts.

### ACKNOWLEDGMENTS

We would like to thank Mike Jaworski and John Hawley for helpful manuscript reviews and Freeport-McMoRan Copper and Gold, Inc. (formerly Phelps Dodge Mining Company) for allowing us the opportunity to work on this project and also share the results.

### REFERENCES

- American Society of Agronomy, 1982. Monograph No. 9, Methods of Soil Analysis: Soil Science Society of America, Inc., Madison, WI.
- Babcock, J.S., 1953, Mining operations of the Hanover mine: Mining Engineering v. 5 p. 1229-1230.
- Hernon, R.M. and W.R. Jones, 1970, Ore Deposits of the Central Mining District, Grant County, New Mexico, *In* Ridge, J.D., ed., Ore Deposits of the United States, 1933-1967: American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. New York, p. 1211-1238.
- Hillesland, L.L., R.B. Hawkins, and W.T. Worthington, 1995, The Geology and mineralization of the Continental mine area, Grant County, New Mexico, *In* F.W. Pierce and J.G. Bolm, eds., Porphyry Copper Deposits of the American Cordillera: Arizona Geological Society Digest v. 20 p. 473-483.
- Jennings, S.R. and D.J. Dollhopf, 1995, Acid-base Account Effectiveness for Determination of mine Waste Potential Acidity. *Journal of Hazardous Materials* v. 41. pp. 161-175.
- Park, C.F. and R.A. MacDiarmid, 1975, Ore Deposits. W.H. Freeman and Co., San Francisco, p. 268-288.
- Price, W, 1997, Draft Guidelines and Recommended Methods for the Prediction of Metal Leaching and Acid Rock Drainage at minesites in British Columbia. Ministry of Employment and Investment (Ministry of Energy and Mines), Victoria, British Columbia (April). 143 p.
- Sobek, A.A., W.A. Schuller, J.R. Freeman, and R.M. Smith, 1978, Field and Laboratory Methods Applicable to Overburdens and mine Soils: Environmental Protection Agency Report EPA-600/2-78-054. U.S. Gov. Print Office, Washington, DC.