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Notes

Geochemistry of soil contamination from lead smelters near Eureka Nevada

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ABSTRACT: Eureka, Nevada, was once a boom-mining town with peak production of Pb, Ag, and Au between the 1870s and 1890s. Most of the ores from the area were processed in two smelters located at the north and south edges of the town. Smelter effluent was exhausted in the vicinity of the smelter furnaces with little regard to potential health concerns.

For this study, 186 soil samples from sites in the area surrounding Eureka were analysed for 43 elements. Factor analysis and element plots identified 16 smelter-related elements: Ag, As, Bi, Cd, Cu, Hg, In, Mo, Pb, S, Sb, Sn, Te, Tl, W, and Zn. Eight other elements (Ba, Be, Co, Cr, Mn, Ni, U, and V), whose distributions are controlled by the chemical composition of the underlying substrate material, were also evaluated.

Of these 24 elements, only six (As, Cd, Pb, Tl, Sb, and Mn) had concentrations that exceeded U.S. Environmental Protection Agency (EPA) estimated residential soil screening levels considered to represent possible health risks. For some analysed elements (In, S, Te, and W) no screening levels have been established. Whether these elements, or any of the others determined, constitute a health risk in the local population is not known.

SUPPLEMENTARY MATERIAL: Analyses for 43 elements in 186 soil samples are available at www.geolsoc.org.uk/SUP18673

KEYWORDS: *lead, arsenic, cadmium, mercury, thallium, soil samples, Nevada, smelter contamination, health risks*

Eureka, Nevada, was one of the many significant boom-mining towns that sprang up in the early days of the settlement of the western United States. Early (pre-1900) mining and smelting in the Eureka area (Curtis 1884; Winzeler & Peppin 1982) were commonly conducted with little understanding of the effects of mining activity on the environment or human health. As a result, mine dumps were generally located adjacent to mine portals, regardless of drainage considerations or proximity to housing. Likewise, structures for treating ores—mills and smelters—as well as slag piles, were generally constructed close to the sources of ores or to railroads (Earl 1988). The effects of the dispersion of liquid or particulate effluents from these smelter locations were thus not seriously considered in locating these structures. As a result, the potential remains for health risks from these historic mining and processing operations.

A geochemical prospecting study in the extreme northern part of the Eureka mining district was published by Miesch & Nolan (1958). A geochemical evaluation of the elements associated with the ores in the entire Eureka district (Chaffee 1987) showed that a number of elements associated with health risks were present in high concentrations in soils from many parts of the district, including sites near the town of Eureka. The present investigation was undertaken to further evaluate these earlier observations.

The primary goal of this current investigation has been to: (1) identify the chemical components of the smelter effluents in soils of the Eureka area; (2) determine the distribution and total concentrations of these elements; and (3) for selected elements, compare the range of values determined to estimated values deemed to represent potentially unacceptable risk levels. The health risks, if any, and the chemical forms of these contaminants have not been identified but remain as a consideration for future study.

GEOGRAPHICAL AND CLIMATOLOGICAL SETTING

Eureka, the county seat of Eureka County, Nevada, is located in the east-central part of Nevada (Fig. 1), on U.S. Highway 50. The nearest large towns are Ely, c. 126 km to the east, and Elko, c. 182 km to the north-NE. At the height of the mining boom in 1878, the population of Eureka peaked at 9000 (Earl 1988). The current population of Eureka is c. 1900 (Eureka County, Nevada 2012). Elevations in the study area range from c. 1865 m on the north edge of the study area, in Eureka Canyon, to c. 2560 m on Prospect Mountain, in the southwestern part of the area (Fig. 2).

Climate summary data for the National Oceanic and Atmospheric Administration weather station in Eureka for

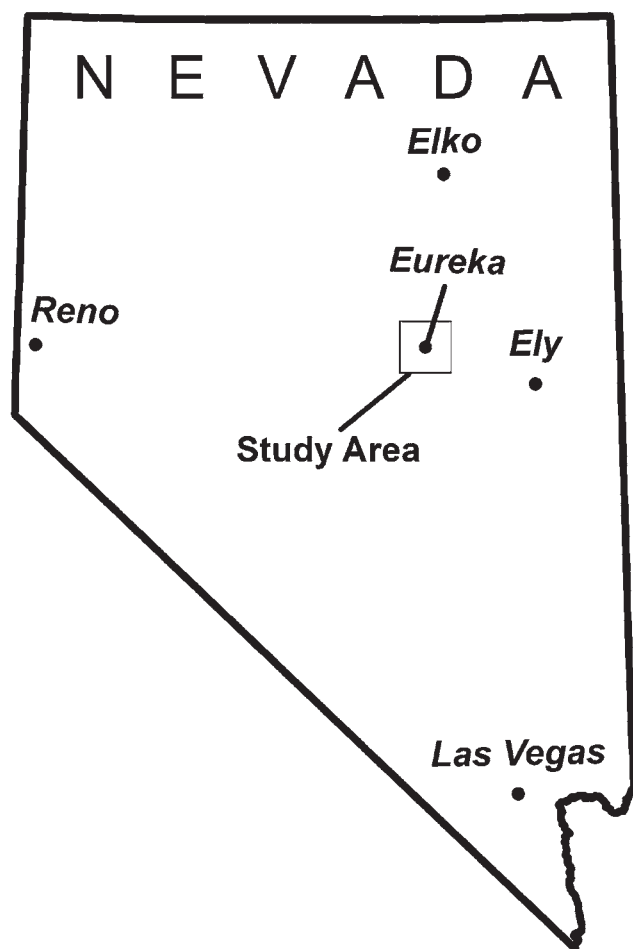


Fig. 1. Map of Nevada showing location of the study area.

most of the period of 1952–2011 show an average annual maximum temperature of 15.4°C and an average annual minimum of 0.4°C, with a mean of 8.1°C. Extremes during the period were -29.4°C and 37.2°C. Mean annual total precipitation for that period was 298 mm, which includes an average annual total snowfall of 1113 mm. Extreme annual precipitation varied from 582 mm to 143 mm. Precipitation is not distributed evenly; the wettest month is May and the driest, July (Western Regional Climate Center 2011).

GEOLOGICAL SETTING

The Eureka mining district is in the Nevada part of the Basin and Range Physiographic Province of the United States. The geology of the mining district and vicinity has been described in detail elsewhere (Hague 1883, 1892; Nolan 1962; Nolan *et al.* 1971, 1974; Dilles *et al.* 1996; Vikre 1998) and is only summarized here. The area included in the present study covers the part of the district around the town of Eureka and to the north comprises mostly Tertiary and Quaternary gravels and Quaternary alluvium (Fig. 2). Directly east of the town of Eureka, the hill-sides are largely composed of andesites of the Tertiary Richmond Mountain Andesite (Nolan 1962; Nolan *et al.* 1971; 1974). Also present both to the east of Eureka and in scattered localities in and west of Eureka are small outcrops of a white, air-fall bedded tuff and intrusive rhyolite that are included in the Tertiary Pinto Peak Rhyolite. These two Tertiary-aged units are shown on the geological map (Fig. 2) as 'Volcanic rocks, undivided (Tertiary)'. None of the above units is mineralized. The south and west

parts of the study area include outcrops of the Newark Canyon Formation (Cretaceous), the Carbon Ridge Formation (Permian), the Diamond Peak Formation (Mississippian), and the Chainman Shale (Mississippian), all of which are included in the unit on the geological map labeled 'Sedimentary rocks, undivided (Cretaceous and Permian to Mississippian)'. None of these pre-Tertiary units is mineralized.

South and/or west of Eureka are locally mineralized units, including the Hanson Creek Formation (Ordovician), the Pogonip Group (Ordovician), and the Eureka Quartzite (Ordovician), shown on the geological map (Fig. 2) as "Sedimentary rocks, undivided (Ordovician)", and small zones containing dikes and sills of quartz-rich porphyritic rocks (shown on the map as "Quartz porphyry dikes (Cretaceous)"). The Eldorado Dolomite and Hamburg Dolomite, also south and west of Eureka, comprise most of the unit "Sedimentary rocks, undivided (Cambrian)" and are the most important ore hosts in the district.

MINERAL DEPOSITS

During the period in which the smelters were operating, mining in the Eureka district was mostly of ores of Pb, Ag, and Au. In addition to these three elements, analyses of these ores reported the minor and trace elements As, Bi, Cd, Cl, Co, Cu, Hg, Mn, Mo, Ni, P, S, Sb, Se, Sn, W, and Zn, as well as the major elements Al, Ca, Fe, Mg, and Si (Curtis 1884; Hague 1892; Nolan 1962; Vikre 1998). Most of the ores mined consisted of highly oxidized minerals; sulphide minerals were only a minor part (Curtis 1884; Nolan 1962).

In an earlier study of the mineral deposits of the Eureka area (Chaffee 1987), R-mode factor analysis identified two distinct element suites related to the mineral deposits. The first suite of elements included Ag, Cu, Pb, Sb, and Zn, and the second, As, Au, Hg, and Sb. The major deposits of the district exploited in the 19th century were mostly associated with the first suite. These were mainly polymetallic carbonate-replacement deposits (Morris 1986; Vikre 1998) that were formed during the Cretaceous Period (Shawe & Nolan 1989). The second suite, whose elements spatially overlap the first suite in some localities, is deemed to be related to Tertiary-aged Carlin-type Au deposits (Shawe & Nolan 1989), which commonly contain anomalous amounts of the elements Au, As, Hg, and Sb, and often contain anomalous amounts of a number of other elements, which may include Ag, Ba, Bi, Cd, Cu, F, Mo, Pb, Se, Sn, Te, Tl, W, and Zn (Berger 1986; Guilbert & Park 1986; Christensen 1993; Doyle-Kunkel 1993; Margolis 1997; Nutt *et al.* 2000; Mathewson 2006).

HISTORY OF MINING AND SMELTING

The area included in this study (Fig. 2) covers only a small part of the Eureka mining district as described by Nolan (1962). Silver-rich deposits were first discovered in the district in New York Canyon in 1864. The peak production of mining was between about 1870 and 1880. By the 1890s, most of the bonanza Pb-Ag ore bodies were exhausted, and mining of these deposits largely ended by 1898 (Earl 1988). Mining around Eureka for both base and precious metals continued intermittently on a smaller scale throughout the 20th century and continues to the present day. A major Carlin-type Au deposit is currently being mined just west of the area investigated for this study (Russell 2006).

The high-grade Pb-Ag ores of the Eureka district were mostly contained in weathered gossans present in host rocks composed of limestone or dolomite. At the time of the initial discovery of the ores in 1864, no established technology existed to recover the Pb and Ag from this strongly oxidized ore material (Winzeler & Peppin 1982; Earl 1988). In 1869, a

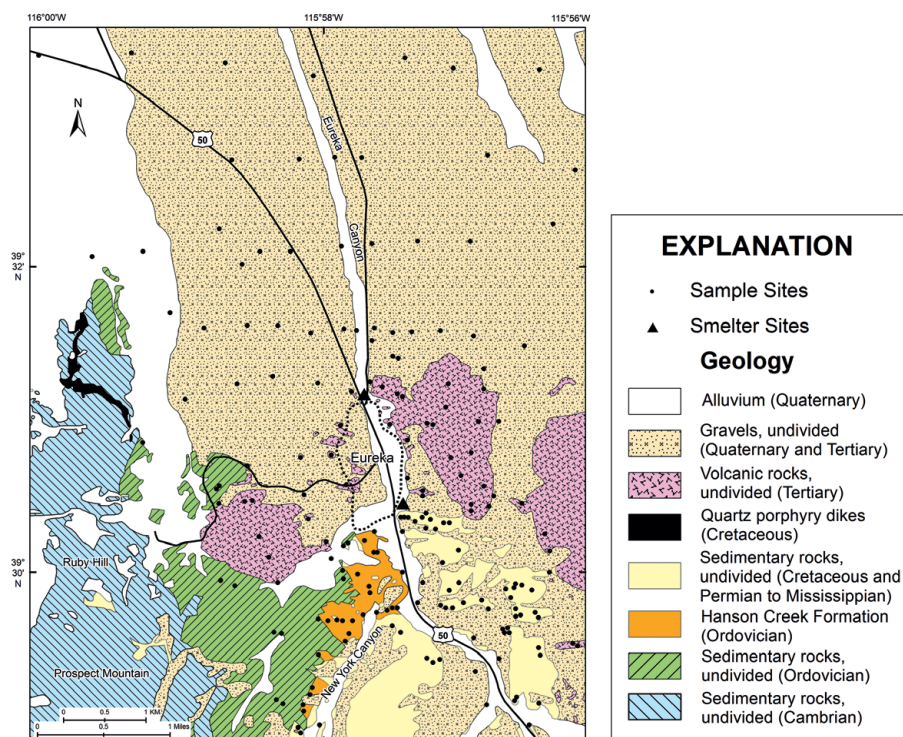


Fig. 2. Generalized geological map of the study area, Eureka County, Nevada. Sites for soil samples are shown as black dots. Geology modified from Nolan (1962), Nolan *et al.* (1971), and Nolan *et al.* (1974).

method was perfected to mill and smelt these ores, and eventually 19 smelters were constructed in and near Eureka. Of these, the Richmond Consolidated smelter and the Eureka Consolidated smelter were the largest. During the 1870s, the Richmond Consolidated smelter was built at the south end of town, and the Eureka Consolidated was built at the north end (Earl 1988; James 1988). Figures 3a, 3b, 4a, and 4b are photographs showing the sites of these two smelters circa 1880 and these same two areas in 2007. Because of the continued decline of recoverable ores and of the price of Pb and Ag after 1880, the Richmond Consolidated smelter ceased operations in 1889, followed by the Eureka Consolidated smelter in 1891.

During the early period of operations of these two smelters, the solid effluents were simply exhausted through stacks directly above the smelter furnaces. During the peak production years, Eureka was described as the 'Pittsburgh of the West' (Winzeler & Peppin 1982; James 1988). The effects of the particulate effluents on the health of the citizens from Pb (and probably other ore-related elements) were predictably detrimental, and as a result, the smelter operators in 1872 added flue stacks that ran up the hillsides near the two major smelters to raise the level at which the effluent was dispersed (Earl 1988). These stacks can be clearly seen in the old photographs (Figs 3a, 4a). Nothing remains of the structure of the flue stack for the Eureka Consolidated smelter (Fig. 3b). However, the grooves dug in the ground to support the flue stacks of the Richmond Consolidated smelter are still present south of the site (Fig. 4b). Significant piles of slag from the two smelters remain to this day at each end of town (Figs 3b & 4b).

SAMPLING AND ANALYSIS OF SOILS

Soil samples were collected in the Eureka area, mostly between 1971 and 1973, with additional follow-up sampling conducted

in 1983 and 2007. The chemical analyses and results of a study of the geochemistry of the mineral deposits were published in papers by Chaffee (1980, 1987) and Chaffee *et al.* (1978).

Soils in the Eureka area are mostly azonal aridisols (Soil Survey Staff 1999), or desert soils (Levinson 1974), which consist mostly of relatively thin deposits of C-horizon material with little organic material. Soils overlying areas of bedrock are generally composed of weathered material derived from the subjacent bedrock. Those soils overlying gravels and alluvium generally reflect the many rock units that make up the substrate material.

Pilot studies and district-wide sampling conducted for the earlier mineral-deposit study Chaffee (1980, 1987) indicated that the fine (<0.063-mm) fraction of a soil sample collected at a depth of *c.* 10 cm tended to best exhibit the effects of smelter contamination. Soil sites for the current investigation were located along traverses in the northernmost part of the study area and at sites in the rest of the area where access to public lands and highway rights-of-way was available (Fig. 2). Both the old and new soil samples used for the current study were collected mainly at depths between *c.* 5 and 20 cm. The uppermost material at each site was discarded to avoid including any anthropogenic trash or traces of organic A-horizon material. In order to best represent the typical the chemical composition of material in the vicinity of a given sampling site, material was composited from 2 to 3 sites within *c.* 5 m of each location plotted on the accompanying maps (Figs 2 & 5 to 9). To the best of our knowledge, all soil samples were collected on public lands. Thus, we have no soil data for the residential or commercial areas within the town of Eureka.

Of the 186 soil samples included in this study, only 28 (15%) were collected from sites where the underlying bedrock was considered to have been altered and/or mineralized. These sites are all confined to outcrops of the Hanson Creek Formation in New York Canyon (Fig. 2). The rest of the samples were collected over Tertiary- to Quaternary-aged gravels

(a)

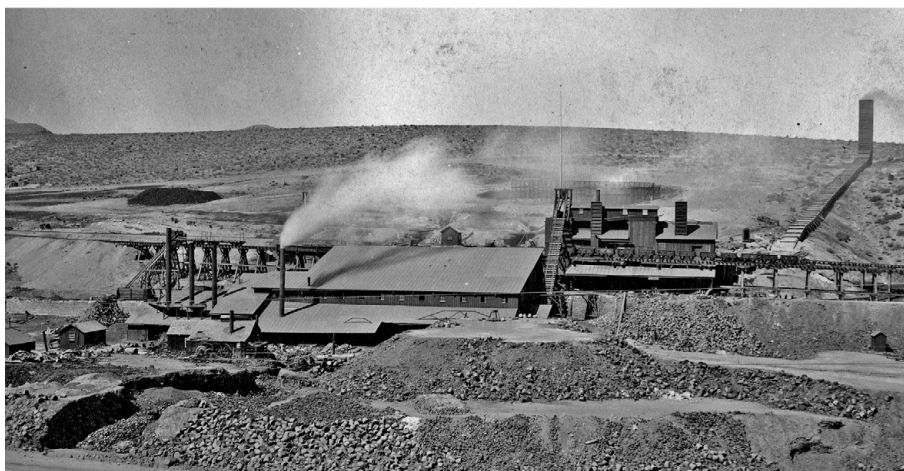


Fig. 3a. Photograph of the Eureka Consolidated smelter, circa 1880. The smelter effluent stack is in the right background. Photograph by permission of the University of Nevada, Reno, archives.

(b)



Fig. 3b. Photograph of the Eureka Consolidated smelter site and slag pile, 2007. U.S. Highway 50 cuts through the remaining slag pile in the middle of the picture.

or alluvium, or over outcrops of unmineralized bedrock (Fig. 2). Thus, anomalous concentrations of ore-related elements that were found in most of the soil samples are deemed to be entirely anthropogenic; that is, the result of smelter effluent contamination or of contamination caused by material falling, or blown, off of ore-transport wagons or rail cars.

In the laboratory, the bulk samples collected in 2007 were sieved using stainless steel screens in aluminum frames. The <0.063-mm fraction was submitted to the laboratory for analysis. Samples collected prior to 2007 had been previously prepared in a similar fashion and archived. These earlier samples were recovered from the U.S. Geological Survey sample storage facility in Denver, and an aliquot was taken for analysis for the present study after each sample was thoroughly re-mixed.

The samples were submitted for analysis in a random order. A U.S. Geological Survey internal standard (SARL, SARM, or SONE) (D.L. Fey, pers. comm. 2013) and soil duplicates were included in each batch of 50 or less samples to monitor the quality of the analyses. The samples were analysed for their 'near-total' (HF-based acid extraction) element content of 43 elements that were included in commercial analytical packages.

These analyses are considered to be 'near-total' because they do not yield the total content of some elements present in resistant minerals (e.g. Cr in chromite, Sn in cassiterite, or U in zircon).

The samples were first decomposed at low temperature using a mixture of HCl, HNO₃, HClO₄, and HF and then analysed for 42 elements (Ag, As, Al, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Sn, Sr, Te, Th, Ti, Tl, U, V, W, Y, and Zn), based on the inductively coupled plasma-mass spectrometry (ICP-MS) method of Briggs & Meier (2002) and the inductively coupled plasma-atomic emission spectrometry (ICP-AES) method of Briggs (2002). The samples were also analysed for Hg by a cold-vapor atomic-absorption method (Brown *et al.* 2002). The analyses for the soil samples are included as Supplementary Material.

RESULTS

Chemical composition of the soils

Table 1 summarizes data for 43 elements determined in 186 soil samples. It tabulates the range of reported values for each element, as well as the number and percent of samples with

(a)



Fig. 4a. Photograph of the Richmond Consolidated smelter, circa 1880. Note effluent stacks on the denuded hills in the upper left and right background of the photograph. Photograph by permission of the Eureka Sentinel Museum, Eureka, Nevada.

(b)



Fig. 4b. Photograph of the Richmond Consolidated smelter site, 2007. This view is a close-up of the hill on the right in Figure 4a.

values between the upper and lower limits of determination (unqualified values), median values for these samples (column A), median values computed for 356 non-mineralized soil samples collected in the Eureka area outside of the study area from the data in Chaffee *et al.* (1978) (column B), and median values computed for a state-wide database of 171 Nevada soils (D.B. Smith, pers. comm. 2012) (column C). The values in column C provide data for some elements not included in the database for the Eureka area listed in column B. The median values are deemed to provide the best measure of the typical value for each element (Reimann *et al.* 2008).

Ratios of the Eureka soil median values to their respective median values in the non-mineralized Eureka samples (column A/B) and the Nevada soil data base (column A/C) are also included. Columns A/B and A/C in Table 1 give an estimate of the relative enrichment of each element in the soils of the Eureka area.

Factor analysis

The analyses for the soil samples were evaluated first by using factor analysis and then by plotting the concentrations of

selected elements identified in that analysis. Factor analysis is a mathematical technique that is used in geochemistry to describe the covariance relationships among the element concentrations in terms of a few underlying, but unobservable, quantities called factors (Johnson & Wichern 2007). The relative degree to which a given element concentration associates with a given factor is its factor loading value and the degree to which a given sample associates with a given factor is called the factor score. Further details concerning factor analysis and its applications to geochemical problems can be found in the literature (e.g. Davis 1973; Howarth 1983; Reimann *et al.* 2008).

Before the factor analysis was run on the data-set, all qualified values—those reported by the analysts as being below the lower limit of determination—were replaced by a value equal to 0.5 times the reported qualified value. The ‘principal factor analysis’ method was used with a varimax rotation (Reimann *et al.* 2008). In this analysis, all values were transformed to natural logarithms, and the resulting values for each element were further transformed by subtracting their respective means and dividing by their standard deviations. A 4-factor model was selected as best representing known geological conditions in the study area. The criteria described by Reimann *et al.* (2008)

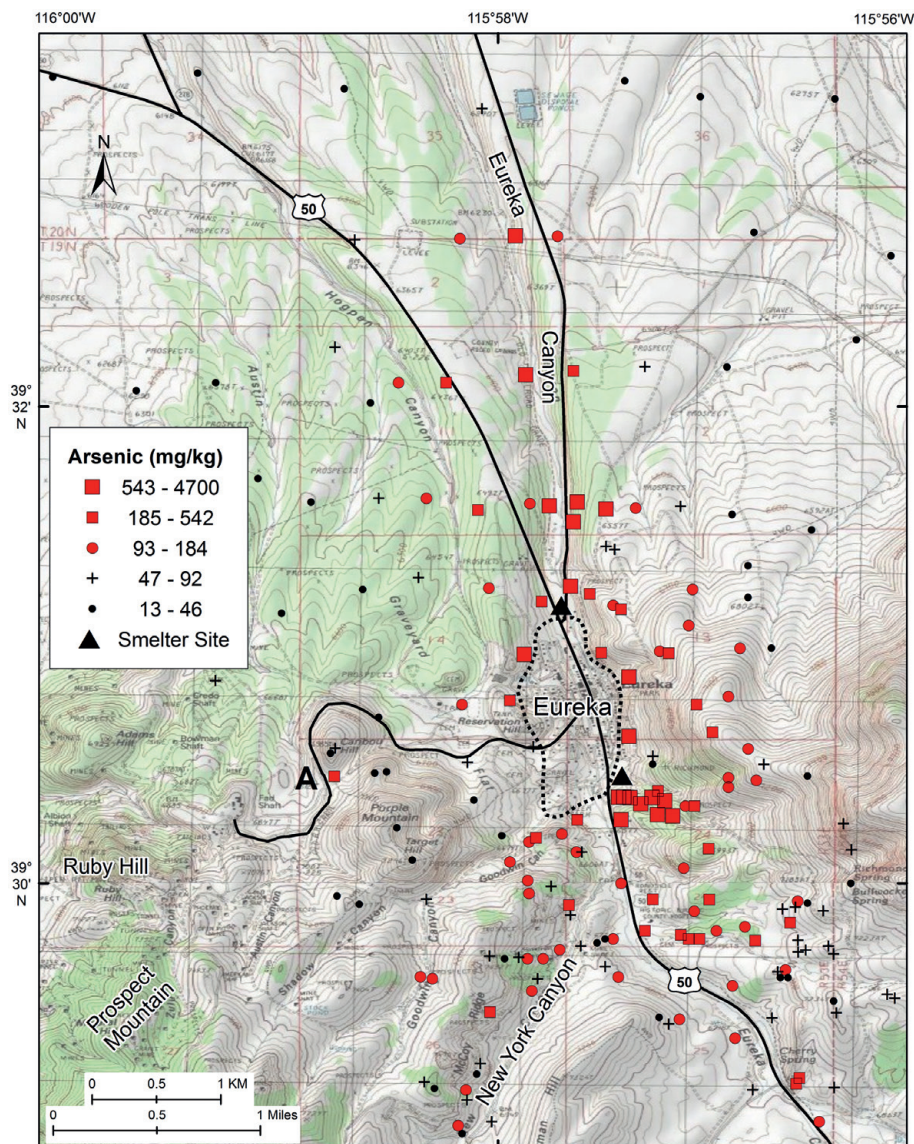


Fig. 5. Topographic map showing distribution of soil concentrations for As. Site A is described in the text. Details of the geological units are given in Figure 2.

require that the number of samples for a robust factor analysis be at least eight times the number of elements in a given data-set. Clearly, our data-set (186 samples and 43 elements) does not meet this standard and thus must be viewed with caution.

For the present study, the factors produced were examined to see if any of them contained the same group of elements that were known to be associated with the local ores, and hence, the smelter effluents. Table 2 shows the factor loading values for this 4-factor model with the elements listed in order of their factor loading values. Most elements are assigned to just one of the four factors. However, three elements (Fe, P, and Ti) are partitioned between two factors, indicating that there is more than one major source for these elements. This model accounts for 78% of the variance in the data.

Factor scores were also determined and were plotted on the geological base map of the study area. For each factor, the distribution of the highest positive factor scores gives a good indication of what each of the four factors represents chemically or geologically. Factor 1 (Table 2) represents the ore- and smelter-related elements. The highest positive score values for

this factor are for samples closely associated spatially with the locations of the two principal smelter sites. Factor 2 is a lithology-related factor whose highest scores are most closely related to samples collected over the Tertiary volcanic rocks and the Diamond Peak Formation, as well as to gravels derived from these formations. Samples with high scores for Factor 3 are also associated with specific lithologies, mainly the carbonate- and clastic-rich beds of the Diamond Peak Formation, the Carbon Ridge Formation, and the Newark Canyon Formation, respectively. The highest scores for Factor 4 are for samples collected mainly in New York Canyon and associated almost entirely with one carbonate-rich lithology, the Hanson Creek Formation (Fig. 2).

Distributions of smelter-related elements

The soil analyses for all of the elements were plotted on a shaded-relief, topographic base map of the study area, with the total range of values for each element assigned to one of five classes, divided at the 25th, 50th, 75th, and 90th percentiles.

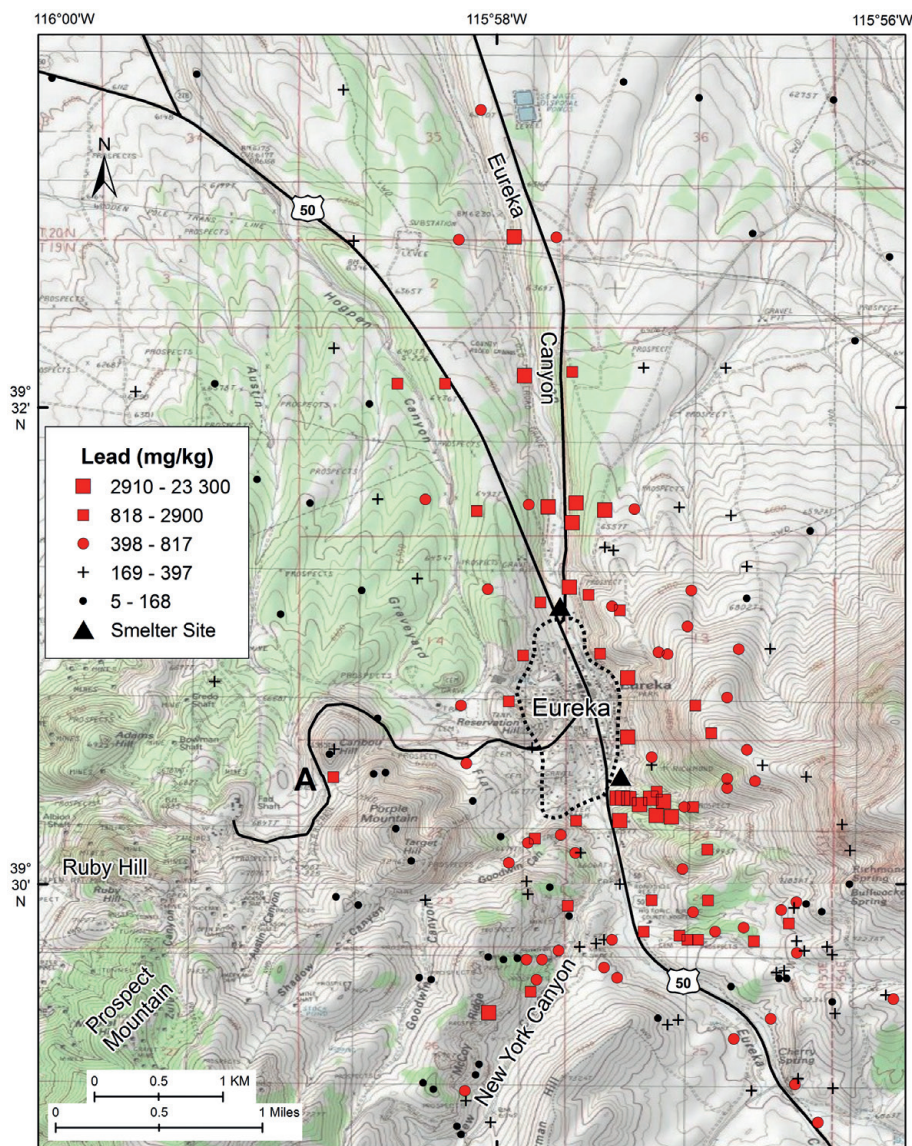


Fig. 6. Topographic map showing distribution of soil concentrations for Pb. Site A is described in the text. Details of the geological units are given in Figure 2.

Evaluation of the spatial distributions of sites with anomalous values for the 43 elements confirms that the first 16 of the 18 elements in Factor 1 (Ag, As, Bi, Cd, Cu, Hg, In, Mo, Pb, S, Sb, Sn, Te, Tl, W, and Zn) (Table 2) are strongly associated with smelter contamination. All these elements show concentration levels that are generally highest near the smelter and slag-pile sites and decrease with distance from the two smelter sites. Plots of the analyses of the remaining 27 elements did not exhibit anomalies that could be spatially related to this contamination.

For this paper, plots for four elements known to be associated with health risks (As, Pb, Cd, and Hg) are included (Figs 5–8). These four show similar distributions, as does the plot for Sb, which is not included here. Also included is a plot for Tl (Fig. 9), which shows a somewhat different distribution pattern. Samples with values in each class are shown on the maps with a common symbol. By examining each map, one can get a sense of where the highest and lowest concentrations for each element are located. In some cases the outer distribution of sites with anomalous concentrations for an

element is not well established because sampling did not extend far enough from the smelter or mineralized rock sites for the concentration of such elements to decline to background levels. Additionally, we have no data points within the residential or commercial parts of Eureka, so we are unable to evaluate those areas as part of our investigation.

Because the town of Eureka is situated in a roughly north-south valley, the generally elongated distribution of samples with anomalous concentrations is largely dictated by the surrounding topography, as well as by the location of the two main smelters and by the prevailing winds. The highest concentrations for most of the anomalies in the north are centered over and north of the site of the Eureka Consolidated smelter and its associated slag pile rather than at the site of the added smelter stack. That stack was higher on the hill to the west of the actual smelter site (Fig. 3a), suggesting that most of the contaminants present today probably resulted from dispersion of material from the original smelter stacks and the slag pile and not from the added smelter stack. However, the exact site of the added stack could not be located, and it is likely that the

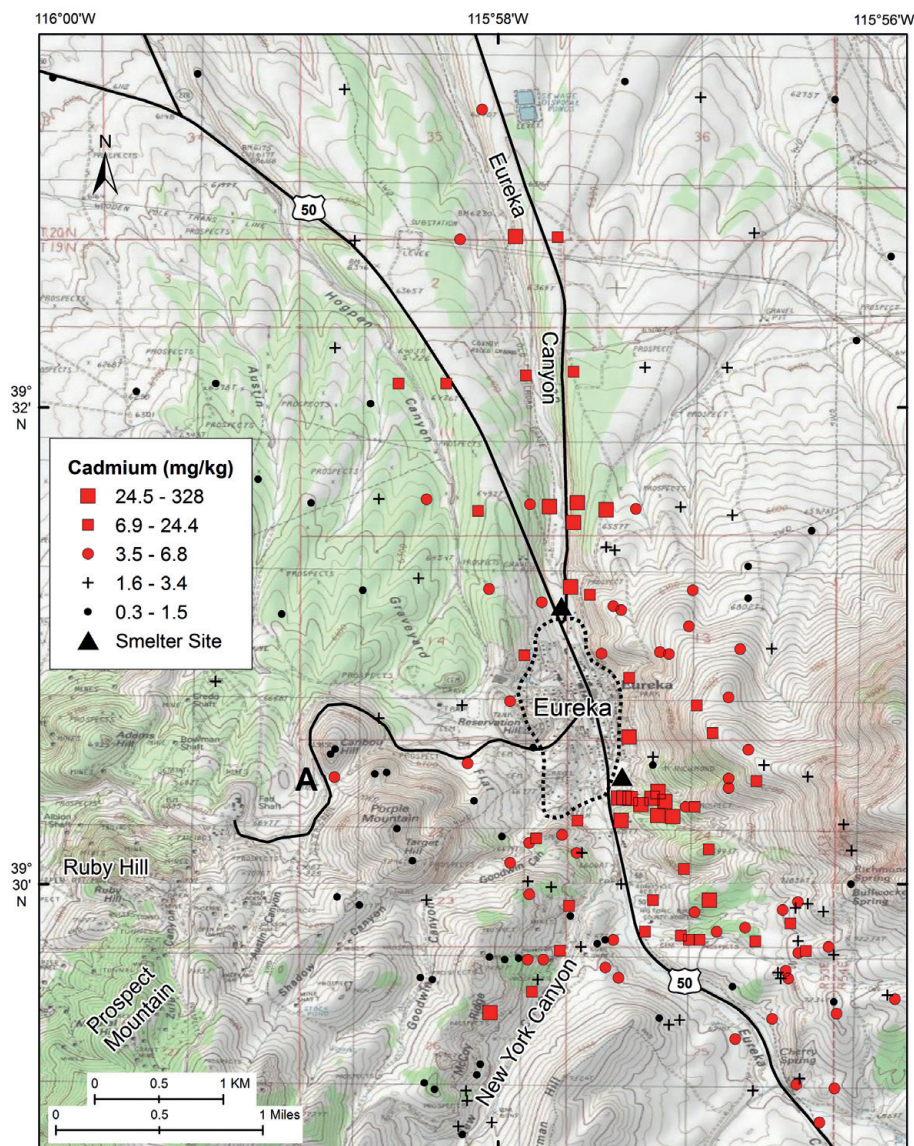


Fig. 7. Topographic map showing distribution of soil concentrations for Cd. Site A is described in the text. Details of the geological units are given in Figure 2.

original surface material in the area where the stack was located has been dispersed or covered up since the smelter was dismantled in the 1890s.

South of Eureka, the sites with the highest concentrations for most elements in the soils are found both northeast and south of the site of the Richmond Consolidated smelter and its associated slag pile. The locations of the added Richmond Consolidated smelter stacks can still be identified on the hill just south of the present county office building. Grooves that held the stacks are partly visible along the side of this hill and behind the slag pile (Fig. 4b).

For most smelter-related elements, a single-site anomaly (labeled 'A' in Figs 5–9) is located to the west of town, along the road to the areas of past mining in the vicinity of Ruby Hill. This road locally follows the route of a long-abandoned railroad that carried ores from the mine sites around Ruby Hill to the smelters in Eureka; so elements that are anomalous at this site are probably related mostly to contamination resulting from material blown, or dropped, off of ore wagons or rail cars.

The five selected smelter-related elements (As, Pb, Cd, Hg, and Tl) are discussed below. For each element the source minerals in the ores are listed, if known, as given in published reports. In the case of the soils, the mineral forms for any of the ore-related elements have not been determined but are probably similar to those described by Bove *et al.* (2011).

Arsenic

In the Eureka district, As tends to be associated with both base- and precious-metal ores and commonly occurs in complex Fe- and Pb-rich sulphosalts. The minerals realgar (AsS), orpiment (As₂S₃), and scorodite (FeAsO₄·2H₂O) were present locally. Arsenopyrite (FeAsS) was identified, mainly at depth in mine workings (Curtis 1884; Nolan 1962).

Concentrations of As in the Eureka area soils range from a low of 13 mg/kg to a high of 4700 mg/kg (Table 1). The ratio of the median Eureka soil value for As to that of the Eureka non-mineralized soil data base (A/B ratio, table 1) is 9.3 and to that of the Nevada soil data base (A/C ratio, table 1) is 10.3.

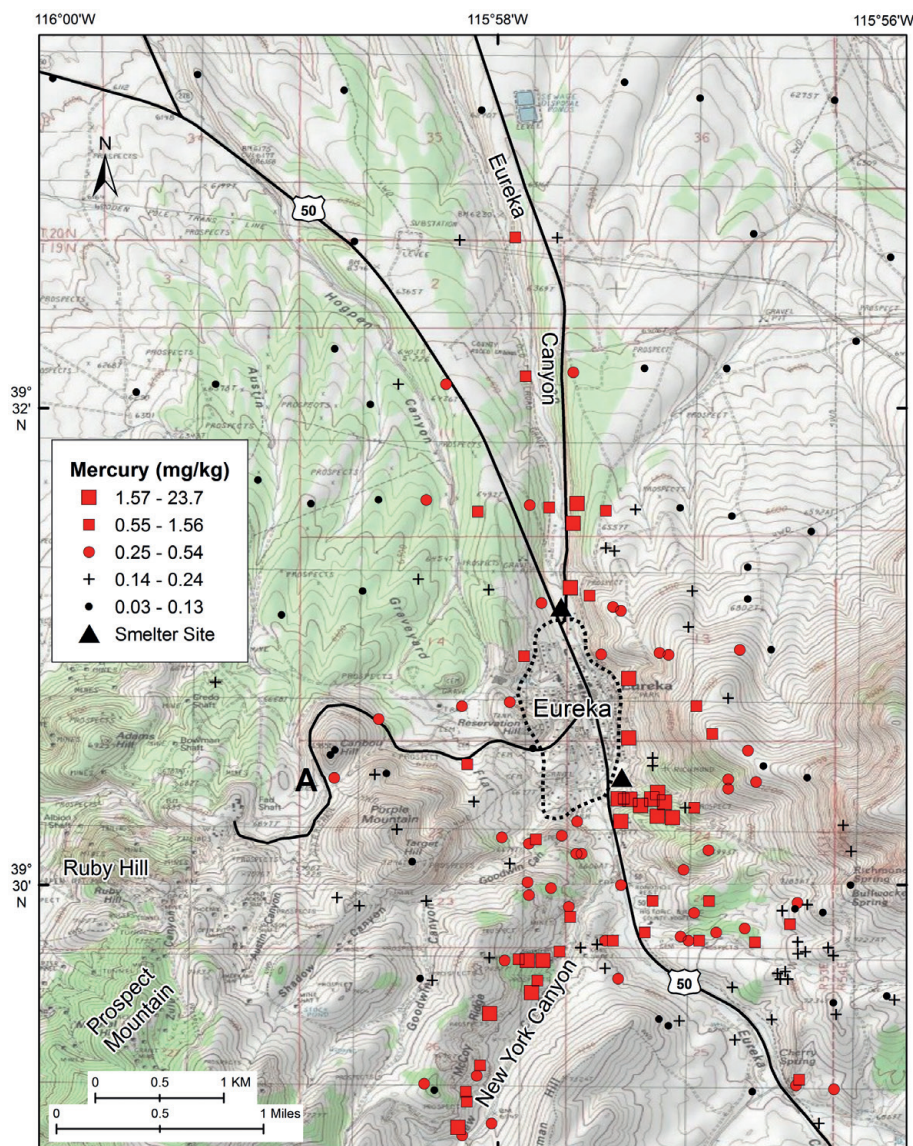


Fig. 8. Topographic map showing distribution of soil concentrations for Hg. Site A is described in the text. Details of the geological units are given in Figure 2.

These high values indicate that As is strongly enriched in the soils collected in the study area.

The distribution of sites with As in soil samples is shown in Figure 5. North of Eureka, samples with the highest As concentrations—those greater than or equal to the 90th percentile value (543 mg/kg)—are from sites located north of the location of the Eureka Consolidated smelter, mainly along Eureka Canyon. South of Eureka, samples with the highest concentrations are from sites located both northeast and south of the site of the Richmond Consolidated smelter. Concentrations generally decrease outwards from the two smelter sites.

Health-related regional screening levels have been established for many elements in water but are not uniformly established for elements in soils. These regional screening levels in soils depend on many factors and thus are difficult to establish with any reliability (Nolan *et al.* 2003). The US EPA has developed regional screening levels (RSLs) for both residential and industrial soils. These RSLs are intended to identify contaminants at a particular site that do not require further Federal attention, and such values alone do not trigger the need for response actions or define unacceptable levels of contaminants in soils. A

soil concentration that exceeds an RSL does not necessarily indicate a health risk: it only means that further study is needed to determine if an actual health risk exists. For some elements two screening levels have been established, each of which corresponds to fixed levels of risk. One level represents a one-in-one million cancer risk (the carcinogenic screening level) and the other represents a non-carcinogenic hazard quotient of 1 (the non-carcinogenic screening level) (US EPA 1996, 2002). Generally for residential soils—those considered here—the carcinogenic screening level will result in a more stringent value than that for industrial sites. A more detailed discussion of these concepts is available at the US EPA website (US EPA 2013).

The US EPA has estimated a concentration of 0.39 mg/kg as the carcinogenic regional screening level for inorganic As in residential soils and 22 mg/kg for non-carcinogenic As in soils (US EPA 2012). In contrast, residential screening levels for potentially unacceptable risk for As in soils in Europe range from 10 to 300 mg/kg, with a median value of 50 mg/kg (Carlson 2007). All 186 of the samples have concentrations that are above the US EPA carcinogenic screening level and most are also above the US EPA non-carcinogenic level.

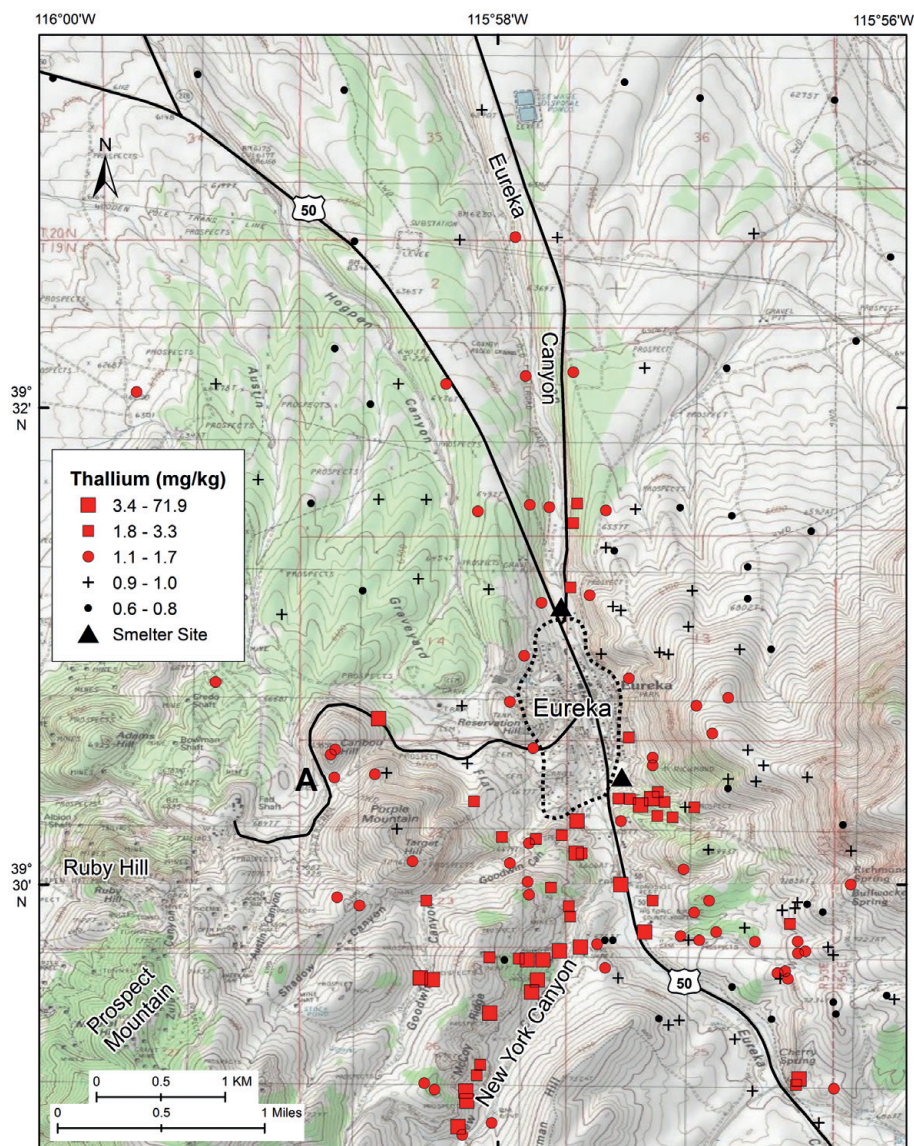


Fig. 9. Topographic map showing distribution of soil concentrations for Tl. Site A is described in the text. Details of the geological units are given in Figure 2.

Based on the distribution of samples with As concentrations greater than or equal to the 25th percentile value (47 mg/kg), the closest value to the estimated European median value (Fig. 5), the northern extent of sites with anomalous As is not completely defined but extends at least 3.7 km north of the Eureka Consolidated smelter site and is centered along the abandoned rail line along Eureka Canyon. To the south of Eureka, samples with ≥ 47 mg/kg As are present for at least 3.2 km southward from the site of the Richmond Consolidated smelter, along both US Highway 50 and New York Canyon. Samples containing As above the 47 mg/kg level are also found as much as 1.1 km to the east and west of the two smelter sites. The eastern extent, in particular, is partly limited by topography. Anomalous As is present at site A (Fig. 5).

Lead

Lead was a major constituent of the base-metal-rich oxidized ores mined in the Eureka district. Lead was found at depth in the mines as the sulphide, galena (PbS), but was more commonly found in

complex, oxidized Pb minerals, such as anglesite (PbSO_4), cerussite (PbCO_3), bindheimite ($\text{Pb}_2\text{Sb}_2\text{O}_6(\text{O}-\text{OH})$), and plumbojarosite ($\text{PbFe}_6(\text{OH})_{12}(\text{SO}_4)_4$). Lead minerals commonly hosted other elements, such as As, Sb, and Ag. Other Pb minerals reported in the Eureka literature include mimetite ($\text{Pb}_5\text{Cl}(\text{AsO}_4)_3$) and wulfenite (PbMoO_4) (Curtis 1884; Nolan 1962).

The concentrations of Pb in soils found in the Eureka area range from 4.7 to 23 300 mg/kg. The A/B ratio for Pb is 7.96 and the A/C ratio is 24.1 (Table 1). Clearly, Pb is strongly enriched in the soils in the study area.

The distribution of sites with Pb in soils is shown in Figure 6. Samples with the highest Pb concentrations—those greater than or equal to the 90th percentile value (2910 mg/kg)—are found north of the Eureka Consolidated smelter site and just south of the Richmond Consolidated smelter site. Concentrations tend to decrease outwards from the two smelter sites. The US EPA has estimated a concentration of 400 mg/kg as the non-carcinogenic screening level for Pb in residential soils (US EPA 2012). Residential screening levels for Pb in soils in Europe range from 100 to 700 mg/kg, with a median value of 450 mg/kg (Carlson 2007).

Table 1. Summary of chemical data for 43 elements in 186 soils, Eureka, Nevada; data in mg/kg unless otherwise noted

Element	Range of values	Number unqualified	Percent unqualified	Median value (A)	356 Eureka non-mineralized soils, median value* (B)	171 Nevada soils, median value† (C)	A/B	A/C
Ag	<1.00–54	118	63	2.00	0.20	<1.00	10	>2.00
Al (%)	0.19–8.08	186	100	6.82	—	6.95	—	0.98
As	13–4700	186	100	93	10	9	9.3	10.3
Ba	51–2030	186	100	852	700	766	1.22	1.11
Be	0.1–5.7	186	100	2.50	1.50	1.9	1.67	1.32
Bi	<0.04–22.5	185	99	0.79	<10	0.17	—	4.65
Ca (%)	0.48–20.4	186	100	1.91	3.00	2.46	0.64	0.78
Cd	0.30–328	186	100	3.50	<20	0.20	—	17.5
Ce	5.0–101	186	100	61.0	—	60.8	—	1.00
Co	1.3–16.2	186	100	8.9	10	8.1	0.89	1.10
Cr	4.0–150	186	100	38	50	21	0.76	1.81
Cs	<5–36	172	92	8	—	7	—	1.14
Cu	7.2–280	186	100	30.3	20	17.6	1.52	1.72
Fe (%)	0.16–4.38	186	100	2.67	3.00	2.38	0.89	1.12
Ga	0.58–23.7	186	100	17.6	—	16.5	—	1.07
Hg	0.03–23.7	186	100	0.25	0.12	0.02	2.08	12.5
In	<0.02–22.3	184	99	0.54	—	0.04	—	13.5
K (%)	0.07–3.21	186	100	2.11	—	2.23	—	0.95
La	3.6–50.7	186	100	31.2	30	32.2	1.04	0.97
Li	1.0–53	186	100	37	—	37	—	1.00
Mg (%)	0.34–12.60	186	100	0.84	1.50	0.98	0.56	0.86
Mn	141–58 900	186	100	687	700	479	0.98	1.43
Mo	0.47–115	186	100	3.35	<5.0	1.09	—	3.07
Na (%)	0.05–1.99	186	100	1.25	—	1.46	—	0.86
Nb	0.30–39.6	186	100	11.4	<20	11.1	—	1.03
Ni	1.9–125	186	100	17.2	20	13.5	0.86	1.27
P	130–1660	186	100	815	—	630	—	1.29
Pb	4.7–23 300	186	100	398	50	16.5	7.96	24.1
Rb	4–215	186	100	105	—	95.3	—	1.10
S (%)	0.01–0.13	186	100	0.04	—	0.03	—	1.33
Sb	1.91–1750	186	100	15.3	3.0	1.23	5.10	12.4
Sc	0.6–18.2	186	100	9.9	10	7.6	0.99	1.30
Sn	0.3–242	186	100	7.3	<10	1.5	—	4.87
Sr	40–1240	186	100	287	200	315	1.44	0.91
Te	<0.10–4.40	151	81	0.20	—	<0.10	—	>2.00
Th	0.6–26.2	186	100	12.8	—	10.3	—	1.24
Ti (%)	<0.01–0.45	185	99	0.28	0.30	0.27	0.93	1.04
Tl	0.60–71.9	186	100	1.10	—	0.50	—	2.20
U	0.6–8.4	186	100	3.1	—	2.8	—	1.11
V	11–189	186	100	83	100	64	0.83	1.30
W	0.50–10.6	186	100	3.0	<50	2.4	—	1.25
Y	3.1–88.3	186	100	18.9	15	17.8	1.26	1.06
Zn	37–3850	186	100	196	100	64	1.96	3.06

*Values calculated from selected analyses in Eureka soil data set of Chaffee *et al.* (1978). †Values calculated from analyses in the Nevada soil data base of Smith, D.B. (pers. comm. 2012). Leaders (—) indicate no meaningful value.

Note: All concentrations are in mg/kg unless (%) is shown after the chemical symbol.

Based on the distribution of samples with Pb concentrations of at least 398 mg/kg, (the 50th percentile value, the closest value to the estimated screening values) (Fig. 6), the northern and southern extents of sites with anomalous Pb are not completely defined. Lead is also anomalous in the sample from site A (Fig. 6).

Cadmium

Cadmium minerals are rare. Rather than forming its own minerals, Cd most commonly occurs in Zn minerals (Wakita & Schmitt 1970; Brehler 1972). At Eureka, Zn, and by inference Cd, was mainly associated with the Ag-rich base-metal ores. In these ores, Zn was commonly found as the oxidized minerals hemimorphite (calamine) ($\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$) and smithsonite (ZnCO_3)

(Curtis 1884). Sphalerite (ZnS) was present at depth in many of the mines (Nolan 1962). Concentrations of Cd range from a low of 0.30 mg/kg to a high of 328 mg/kg (Table 1). The A/B ratio for Cd could not be calculated. The A/C ratio, an approximation for the area, is 17.5, suggesting that this element is strongly enriched in the local soils.

The distribution of sites with Cd in soils is shown in Figure 7. Samples with the highest Cd concentrations—those greater than or equal to the 90th percentile value (24.5 mg/kg)—are found north of the Eureka Consolidated smelter site and both northeast and south of the Richmond Consolidated smelter site. Concentrations tend to decrease outwards from the two smelter sites. The US EPA has not calculated an estimate of the screening level for Cd in soils but gives estimated dietary screening levels of 1800 mg/kg for carcinogenic Cd and 70 mg/kg for

Table 2. Factor loading values for a 4-factor model

Factor 1 (smelter)	Factor 2 (lithology)	Factor 3 (lithology)	Factor 4 (lithology)
As 0.98	Al 0.93	Ni 0.86	Mg 0.85
Pb 0.97	Ga 0.90	Cr 0.80	Ca 0.72
Sn 0.97	Ce 0.90	V 0.78	Mn 0.69
Sb 0.97	Ti 0.89	Cs 0.52	<i>Tl 0.36</i>
Bi 0.97	La 0.86	<i>P 0.35</i>	
Zn 0.96	Th 0.82		
Cd 0.95	Sc 0.82		
In 0.94	Na 0.82		
Ag 0.94	Rb 0.80		
Mo 0.93	Co 0.79		
Hg 0.93	Fe 0.78		
Te 0.92	K 0.76		
Cu 0.91	Be 0.73		
W 0.76	Li 0.69		
S 0.59	Nb 0.62		
Tl 0.59	Sr 0.56		
<i>Fe 0.43</i>	U 0.55		
P 0.37	Y 0.54		
	Ba 0.54		

All values ≥ 0.34 are shown. Secondary values are shown in italics.

non-carcinogenic Cd (US EPA 2012). Residential soil screening levels for potentially unacceptable risk reported for a number of European countries range from 2 to 30 mg/kg with a median value of 6 mg/kg (Carlon 2007), considerably lower than the level given by the US EPA. The extent of sites with soils containing at least 3.5 mg/kg Cd (the 50th percentile value, the closest value to the median value of the European data (Carlon 2007)) are widespread and similar to those of As and Pb. The sample collected at site A (Fig. 7) is also anomalous for Cd.

Mercury

Of the two types of mineral deposits found in the Eureka area, the association of Hg with the Ag-rich base-metal ore deposits in the Eureka district is suspected but has not been established. Mercury is one of the trace elements commonly found in Carlin-type deposits in Nevada (e.g. Margolis 1997), which are present locally in the Eureka district. However, no Hg minerals have been identified in the ores of the district. The concentrations of Hg in soils found in the Eureka area range from 0.03–23.7 mg/kg (Table 1). The A/B ratio for Hg is 2.08 and the A/C ratio is 12.5, indicating that this element is enriched in the Eureka soils.

The distribution of samples with anomalous Hg is shown in Figure 8. Samples with the highest Hg concentrations—those greater than or equal to the 90th percentile value (1.57 mg/kg)—are also present north of the Eureka Consolidated smelter site and in the area northeast and south of the Richmond Consolidated smelter site. Concentrations tend to decrease outward from the two sites. The US EPA has estimated a concentration of 10 mg/kg as the non-carcinogenic screening level for elemental Hg in residential soils and 7.8 mg/kg for methyl Hg in soils (US EPA 2012). Residential screening levels for Hg in soils in Europe range from 1 to 56 mg/kg, with a median value of 10 mg/kg (Carlon 2007).

Unlike some other smelter-related elements, including As, Pb, and Cd, Hg appears to be more anomalous in the New York Canyon area. The reason for this is probably an artifact of the classification scheme used. The distribution of samples with at least 0.14 mg/kg Hg (the 25th percentile value) is widespread and gives a good estimation of the smelter-related dispersion of this element. The southern extent of samples

with this concentration level is not completely defined. The sample collected at site A is weakly anomalous for Hg (Fig. 8).

Thallium

The mineralogical form of Tl in the ores of the Eureka area is not known. In sulphide-rich ores, it is most commonly found in Pb minerals. In oxidized ores, Tl is commonly concentrated in Fe-rich minerals, such as jarosite, and with manganese oxides (de Albuquerque & Shaw 1972). The concentrations of Tl in soils found in the Eureka area range from 0.60–71.9 mg/kg (Table 1). The A/B ratio for Tl could not be calculated. The A/C ratio is 2.20, suggesting that this element is at least weakly enriched in soils of the Eureka area.

The distribution of sites with Tl in soils is shown in Figure 9. This element is distributed somewhat differently from any of the other smelter-related elements. The highest Tl concentrations—those greater than or equal to the 90th percentile value (3.4 mg/kg)—are found entirely in samples collected south of the Richmond Consolidated smelter site, along US Highway 50, and especially in New York Canyon. In contrast to the other selected elements, concentrations at this highest level are not found in the vicinity of the Eureka Consolidated smelter site.

The US EPA has estimated a concentration of 0.78 mg/kg as the non-carcinogenic screening level for Tl, both for a soluble salt in residential soils and for ingested soils (US EPA 2012). For the sulphate and carbonate compounds of Tl in soils, a non-carcinogenic screening level of 1.6 mg/kg is given (US EPA 2002). Based on these values, nearly all samples from the Eureka area contain Tl above the screening levels. Estimates for residential screening levels for Tl in soils in Europe are mostly lacking. Three available values range from 1 to 15 mg/kg with a median value of 10 mg/kg (Carlon 2007), considerably above the US EPA estimates given above. Samples with Tl concentrations most closely matching the 1.6 mg/kg US EPA value are those above the 75th percentile value (1.8 mg/kg) and are found mostly in and near New York Canyon (Fig. 9), as noted above. These observations suggest that the distribution of this element is partly smelter-related and partly associated with the Mn-rich lithology of the altered Hanson Creek Formation (Fig. 2). The factor loading values (Table 2) show Tl loaded on both the smelter-related factor and on Factor 4, which is related to the lithology of the Hanson Creek Formation. Thus, two separate sources are thought to exist to explain the Tl anomalies. The distribution of samples with at least 0.9 mg/kg Tl (the 25th percentile value) is also widespread and gives a good estimation of the smelter- and lithology-related dispersion of this element. The sample collected at site A is anomalous for Tl (Fig. 9).

Of the remaining 11 smelter-related elements for which screening levels are available, only Sb shows concentrations well above the corresponding level estimated to indicate a potential health risk as established by the US EPA or by the European countries cited in Carlon (2007). The distribution of Sb is similar to that of As.

Non-smelter-related elements associated with health risks

Although not thought to be related to the ores and smelter contamination in the Eureka area, eight other elements determined in the soils (Ba, Be, Co, Cr, Mn, Ni, U, and V) are known to be associated with potential health risks to animals and/or humans when present in high concentrations. None of these elements is loaded on the smelter-related factor (Table 2). Plots of these elements are not included here but indicate that there is no obvious spatial relationship of any of them to the smelter sites. The sites with anomalous samples for these elements are either randomly scattered throughout the study area or concentrated in areas of specific lithologies. These highest concentrations are

deemed to be geogenic and close to what would be expected for the lithologies present. The highest concentrations of these elements in the soil samples are thus thought to be solely a result of natural enrichment of these elements by weathering processes or, in the case of Mn, both lithologic and/or mineralization- and weathering-related processes. Of these eight elements, only Mn yielded any concentrations above the non-carcinogenic levels considered to represent a possible health risk (Carlson 2007; US EPA 2012). The sites for samples with unusually high (>1000 mg/kg) Mn concentrations are mostly present well beyond the town limits in outcrops of the mineralized Hanson Creek Formation in New York Canyon (Fig. 2).

Examination of the soil A/B and A/C ratios for these eight non-smelter-related elements shows that, in contrast to most of the smelter-related elements, these eight elements generally have ratios that are well below 2.00 (Table 1), indicating that they are not strongly enriched in the study area soils as compared to local and regional background soil samples. When taken together with the distributions of high concentrations for each of these eight elements, these low ratio values are generally indicative of elements not related to smelter emissions.

DISCUSSION AND CONCLUSIONS

Except where the soils in the vicinity of the town of Eureka have been removed or otherwise markedly disturbed, the present soils still exhibit strong effects of smelter contamination after more than 120 years. Of the 43 elements that were determined in 186 samples of mostly undisturbed soils, moderately to strongly elevated concentrations of 16 elements (Ag, As, Bi, Cd, Cu, Hg, In, Mo, Pb, S, Sb, Sn, Te, Tl, W, and Zn) were found to be smelter-related. All 16 elements exhibit widespread anomalous distributions that clearly show a spatial relation to the locations of the two major smelters that were present in Eureka in the late 19th century, with concentrations highest near the smelter or adjacent slag-pile sites and decreasing outwards. For some elements, the extreme northern or southern extents of their anomalies have not been completely defined.

The soils in the Eureka area contain fine material that has been dispersed naturally as a result of wind and possibly water action. Winds have the potential to transport such material over large distances. During the 1880s, many people were reported to have become ill in Eureka from breathing airborne dust (Earl 1988). The climatological data on wind direction indicate that the predominant wind direction in the Eureka area is from south to north (Western Regional Climate Center 2011). This observation is confirmed by distributions of many of the elements in the soils studied for this report.

As a result of wind action, there may be an increased risk to humans of exposure through either inhalation or ingestion of dusts or ingestion of soils (or possibly plants grown in soils) containing high concentrations of As, Cd, Hg, Pb, Sb, or Tl. While the sources of dust today are not quite the same as during the time of active smelter operations, the effects at present of breathing locally derived dust or particulate material over a long period of time may contribute to a variety of health issues in local residents, especially those who work outdoors. We emphasize, however, that we have no evidence of recent health problems that may be related to any of the elements present in the soils of the Eureka area.

Based on the available data, high concentrations for only As, Pb, Cd, Tl, Sb, and Mn clearly exceed regional carcinogenic and/or non-carcinogenic residential soil screening level estimates given by the US EPA or risk levels established by a number of European countries (Carlson 2007). Such high concentrations may thus present potential human health risks (Paasivirta 2000; Carrizales *et al.* 2006). Of the above five smelter-related elements, Sb has not been

discussed here because it closely follows As, both in its mineral hosts and in its distribution in soils in the study area.

Although clearly high concentrations of many of the 16 smelter-related elements have been identified, caution is needed in interpreting the possible health risk of these elements because no standard procedures have been established for collecting, preparing, or analysing the various soils studied by us or by the government organizations cited above. Much remains to be done to establish standard protocols for evaluating soils (Nolan *et al.* 2003). Additionally, although widespread smelter-related contamination is present in the soils in the vicinity of Eureka, we emphasize that the soil samples for this study were collected from outside of the residential and commercial areas of Eureka, and thus no details can be provided about possible contamination within the town.

The analyses we have discussed for the study area are all near-total element concentrations. The possible health risks of any of the elements found in the Eureka soils are dependent on a number of factors, including the bioaccessibility and bioavailability of a given element, both of which are related to the chemical state of each element (e.g. Spear *et al.* 1998; Paasivirta 2000; Nolan *et al.* 2003; Schaider *et al.* 2007). The study of metal speciation in soils is complex, and progress has been slow in identifying species (Nolan *et al.* 2003). This study has been limited to identifying what elements are present in the soils today and their distributions and near-total concentrations. Bove *et al.* (2011) have determined that soils in the Eureka environment contain both primary and weather-affected, smelter-related minerals, at least some of which are readily bioaccessible. The high concentrations of at least some of these minerals in the Eureka soils, as well as past descriptions of the health effects of Pb emissions on the local population (Earl 1988), suggest that the potential for health risks for humans and animals may still exist in the Eureka area. However, the health effects, if any, of these elements on the local population have not been investigated.

This study is dedicated to the memory of Thomas B. Nolan of the US Geological Survey (USGS), who spent many years studying the geology and mineral deposits of the Eureka mining district and vicinity. Nolan was instrumental in assisting the senior author regarding the history, mining, and geology of the area.

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