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Characterization and implication of potential fugitive dust sources in the Paso del Norte region

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Abstract

A series of analyses were performed to provide chemical signatures for surface soils and to evaluate potential sources of fugitive dust in the Paso del Norte (PdN) region. Eighteen sites were selected for soil sampling based on an assessment of the soil types in the region and the main upwind source areas with a potential for wind erosion. Analyses of the soil samples provided chemical ‘fingerprints’ of the surface soil that are presumed responsible for much of the fugitive dust loading in the region. Analysis of chemical data through multivariate statistical techniques combined with information on lithologic units, soil types, and enrichment factors identified several groups of elements associated with either natural or anthropogenic origins. Cluster analysis and principal components analysis defined four groups of elements while a redundancy analysis implied a strong association between certain elements (Ag, As, Cd, Mo, Mn, Pb, Sb) and an anthropogenic point source in the region. The conclusions from the statistical analyses are further supported by the enrichment factor (EF) analysis, using aluminum as the reference element. That is, a group of presumed anthropogenic trace elements had their highest EFs in the fine size fraction at a site close to the anthropogenic point source. Thus, the statistical analyses of surface soil data provide a useful means for quantifying the extent of anthropogenic perturbations and for highlighting some implications of contaminated fugitive dust sources.

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1. Introduction

Airborne particulate matter (PM) has been identified as the major air pollutant in the PdN region.

This is a bi-national, three-state international community of three cities: El Paso, Texas and Sunland Park, New Mexico in the US, and Ciudad Juárez, Chihuahua, México. The elevated level of PM in the region poses potential health risks to the public, especially sensitive persons including the elderly and those with respiratory ailments (Dockery and

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Pope, 1994; Schwartz, 1994; Ostro et al., 1999; Pope and Dockery, 1999).

Several studies have been conducted recently to characterize PM pollution in the region (Li et al., 1999, 2001, 2003; Jeon et al., 2001; Arrieta et al., 2003; Noble et al., 2003; Paschold et al., 2003). Li et al. (2001) examined the spatial and temporal variations of mass and elemental composition in both fine and coarse fractions of PM, while Jeon et al. (2001) identified sources of PM using the organic PM components of 45 time-resolved samples. The majority of the PdN airborne PM appeared to be inorganic in nature, whether it was naturally occurring or anthropogenic in origin. The US Environmental Protection Agency (US EPA, 2000) and Li et al. (2001) separately reported that the coarse fraction of PM or $PM_{10-2.5}$ (particulate matter with an aerodynamic diameter of less than 10 μm but greater than 2.5 μm) in the PdN region accounts for 75% of the mass detected in PM_{10} (particulate matter with an aerodynamic diameter of less than 10 μm).

The major sources of inorganic PM in the region are fugitive dust from unprotected surfaces including geologic materials from the surrounding desert and unpaved roads, and trace elements from re-suspension of deposited metals previously emitted from several regional point sources. Historically, anthropogenic indicator trace elements (Pb, As, Cd, Cr) have been released from several regional industrial point sources, such as the ASARCO (American Smelting and Refining Company) Smelter on the west side of El Paso, Federal Smelter in central El Paso, and Phelps Dodge copper refinery on the east side of El Paso (TDH, 2001). Lead contamination in air and surface soils is a unique case because leaded gasoline was widely used in the air basin before it was banned in the US in 1985 (MacGregor and Mielke, 1995) and later in 1992 restricted to older vehicles in México (SEDESOL, 1992).

1.1. Study objectives

As part of the 1998 Paso del Norte Air Research Program (PdNARP, Li et al., 1999), studies were conducted to characterize the sources of fugitive dust, such as emissions generated from exposed

granular surfaces by vehicles traveling on unpaved roads and from wind erosion of open fields by wind gusts. The objectives of that program were to: (1) characterize the PM emitted from various unprotected surfaces; and (2) attribute chemicals of anthropogenic origins detected in the soil to the potential sources in the region.

Our study was a component of PdNARP, with a specific aim of chemically characterizing potential fugitive dust sources in the PdN region. We determined element and anion concentrations in eleven particle size categories (ranging from 0.82 μm to $>250 \mu\text{m}$) in the soil and performed enrichment factor and multivariate statistical techniques on a set of 18 elements, including As and Pb, to evaluate anthropogenic perturbations of soils in relation to fugitive dust sources.

1.2. Historical soil data for the PdN region

The chemical composition of surface soil in the PdN region has been studied since 1970 due to health concerns over metals emitted from regional smelters and automobiles. In December 1971, the El Paso City-County Health Department (EPCCHD) reported that large amount of lead and other metals were released into the air by the ASARCO facility. It has been reported that between 1969 and 1971, the smelter discharged 1100 tons of lead, 560 tons of zinc, 12 tons of cadmium, and 1.2 tons of arsenic into the air (Rosenblum et al., 1975). The EPCCHD found also that the mean concentrations of metals were highest downwind of ASARCO and decreased logarithmically with distance from the smelter (Landrigan and Baker, 1981). Additionally, soil samples taken between June and December of 1972 demonstrated that the highest concentrations of lead and other metals in surface soils occurred within 0.3 km of ASARCO (Rosenblum et al., 1975).

As follow-up study by the Centers for Disease Control and Prevention (CDC) showed that the lead concentrations in soils near ASARCO smelter were in the range of 1000–3600 ppm, but it was concluded that the adverse health effects from this were lesser in extent than exposure to lead in household dust (Landrigan et al., 1975). It was

also reported by the CDC that the percentage of children with blood lead levels higher than $40 \mu\text{g dl}^{-1}$ decreased with distance from ASARCO and the spatial distribution of high blood lead levels was similar to the spatial distribution of ambient lead levels found in household dust.

Lead levels in soil were reported to be less than 200 ppm for several small communities south of the ASARCO smelter (Summer, 1972) and between 0.4 and 34.7 ppm in the valley along the Rio Grande (Miller, 1972). A study conducted in 1974 in Anapra, a Mexican community located just across the Rio Grande from the ASARCO smelter (Ordóñez et al., 1976), complemented previous studies, showing that soil samples from gardens, courtyards, and household dust had elevated concentrations of Pb, Cu, Zn, and Cd and that these trace elements were high near the smelter and decreased with distance from ASARCO. Fifty-two percent of children studied within a 1.6 km radius of the smelter had blood lead levels higher than $40 \mu\text{g dl}^{-1}$.

The Texas Commission on Environmental Quality (formerly, the Texas Air Control Board) conducted an arsenic soil study in El Paso County in 1989. High arsenic concentrations (up to 1100 ppm) were observed in the soil collected at the International Boundary and Water Commission, an area identified as being close to ASARCO and directly across from a brick manufacturing facility in Ciudad Juárez, Chihuahua. Overall results showed that arsenic concentrations were high close to ASARCO and declined with distance from the smelter (Dydek, 1990). The observed maximum arsenic concentration was approximately 150 times higher than the average soil arsenic concentration of 7.2 ppm for western US soil (Shacklette and Boerngen, 1984).

Barnes (1993) reported that the concentrations of naturally occurring elements, such as Ba, Ca, Ni, and Se, in surface soil (0–2.5 cm) and sub-surface soil (10–60 cm beneath the surface) were basically indistinguishable at various sites in El Paso County. However, the concentrations of As, Cd, Cu, Pb, and Zn were high at sites around ASARCO and decreased with distance from the smelter.

Ndame (1993) collected and analyzed 78 soil samples at the University of Texas at El Paso (UTEP) campus, and at parks and public schools within a 2 km radius of the campus. Arsenic concentrations (up to 92 ppm) were discovered in the on-campus soil samples. Peak lead concentration of 1500 ppm was found at a location east of ASARCO smelter. The maximum observed concentrations for arsenic and lead were 13 and 79 times higher than their respective background soil concentrations in western US (Shacklette and Boerngen, 1984).

Areas unlikely to be affected by the ASARCO smelter facility showed, in general, no sign of metals contamination. Devanahalli (1994) found in downtown El Paso that the elemental concentrations of As ranged from below the method detection limit (MDL) of 13–92 ppm and that Pb concentrations ranged from its MDL of 17–560 ppm. The maximum values of As and Pb reported in the study were 13 and 27 times higher than their corresponding average soil concentrations given by Shacklette and Boerngen (1984). In the same year, Srinivas (1994) found neither point sources nor large-scale contamination in east and northeast El Paso.

Recently, the EPA surveyed soil concentrations of As and Pb in El Paso County and Dona Ana County (US EPA, 2001). The EPA research team collected 112 surface soil samples from 0 to 15 cm below ground surface for Target Analyte List total metal analyses and reported that: (1) the highest Pb concentrations occurred at several sites located inside UTEP campus; and (2) most of the cases of As levels in excess of the EPA's soil screening level (SSL) of 20 ppm occurred in undisturbed and unvegetated locations. The SSLs are risk-based concentrations calculated using EPA's toxicity data and conservative exposure assumptions. Screening in this context refers to the process of identifying areas and contaminants at a particular site that do not require further action as would be required by the Comprehensive Environmental Response, Compensation and Liability Act (US EPA, 1996).

Fig. 1 summarizes the highest As and Pb concentrations from the four referenced studies made in the last 10 years in comparison to the results

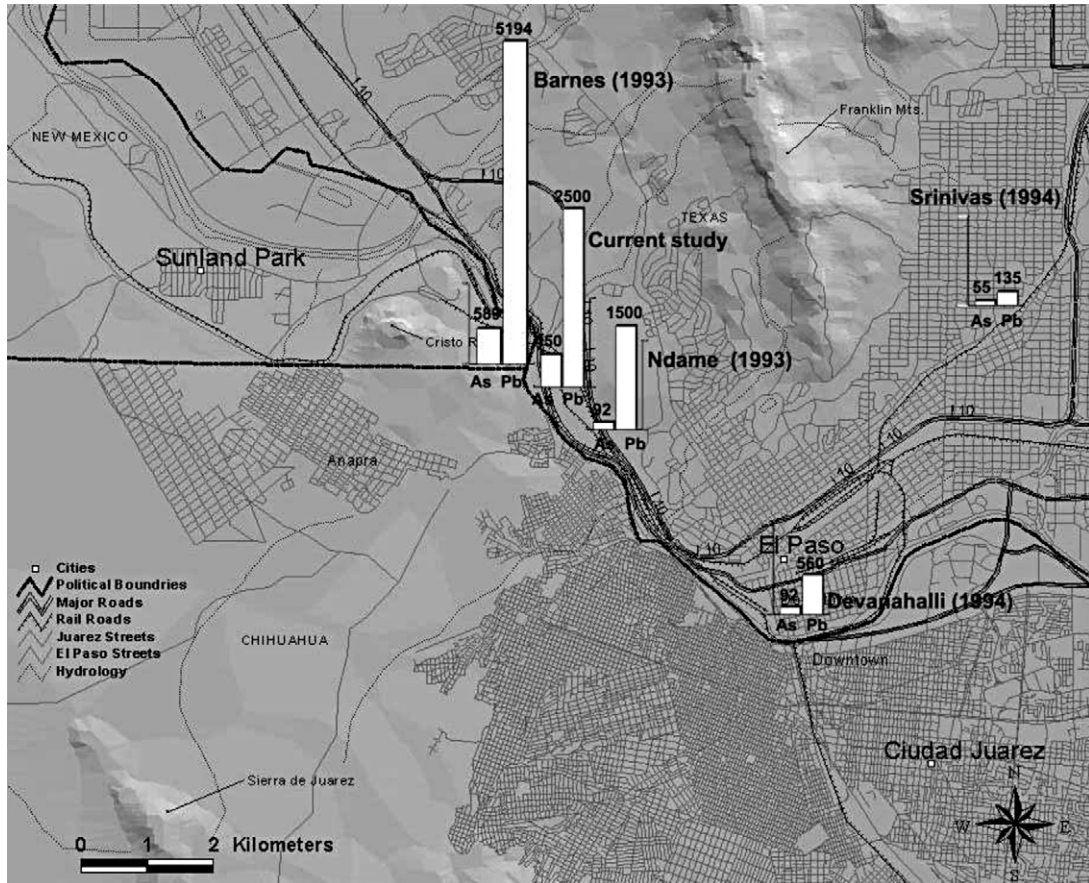


Fig. 1. Highest As and Pb soil concentrations for five surface soil studies in the PdN region.

from the current study. In brief, soil samples have been collected from very localized areas in the PdN region and analyzed for a few target metals, although the large amount of PM suspended from the regional surface soil may actually pose higher health hazards to the public than those few target metals. Systematic characterization of the potential fugitive dust sources in the region could be as important as the analysis of target metals at selected locations.

2. Experimental

2.1. Site selection criteria and main site characteristics

Soil samples were collected at six sites in Ciudad Juárez, Chihuahua and twelve sites in

Texas and New Mexico during February 23–25, 2000. The selection of the sites was based on a meteorological and geographical assessment of the PdN region. The meteorological evaluation was performed to determine the most common wind directions when wind erosion was likely to occur; it was based on 4 years (1991–1994) of hourly surface meteorological data collected at the El Paso International Airport by the National Weather Service. A 7 m s^{-1} h-average wind velocity was selected as the threshold for significant wind erosion for the region (Cowherd et al., 1988; Becerril et al., 1999). Results showed that approximately two-thirds of the winds with velocities greater than 7 m s^{-1} were from 240 to 300° , i.e. flow from the west-southwest through the west–northwest.

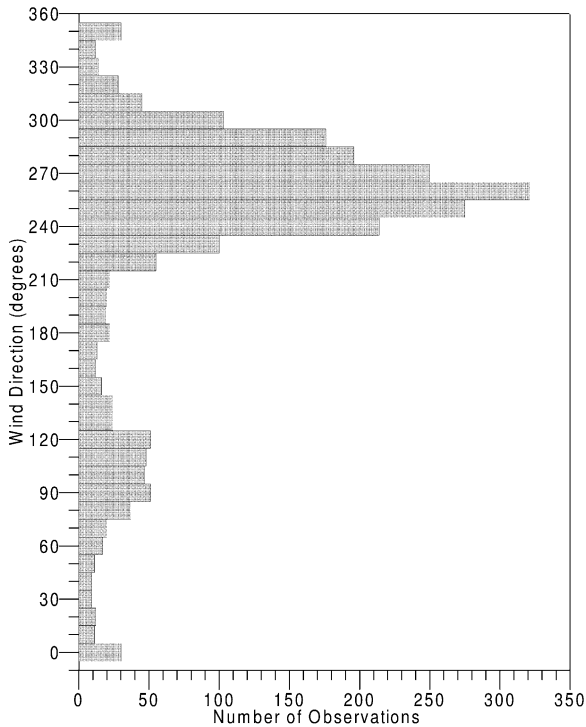


Fig. 2. Number of wind observations collected between 1991 and 1994 with wind speed greater than 7 m s^{-1} vs. wind direction.

Another 10% of the winds were between 80 and 120° , roughly between east and southeast. On the basis of this analysis, areas that are often upwind of the PdN area during high wind events were favored in the site selection. Fig. 2 shows the number of wind observations with wind speeds greater than 7 m s^{-1} with respect to wind direction while Fig. 3 shows the chosen sampling sites.

A geographical analysis was performed to provide spatial representations of land use/land cover, political boundaries, wind erosion potential, soil texture, and major highways in the air basin. Soils data were downloaded from the US Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) web site at a 1:250 000 scale (USDA-NRCS, 2000). For each map unit, a simple weighted-average scheme was used to obtain a soil surface texture and a wind erodibility group (WEG) for each type of soil. WEG is related to the wind erodibility index and is given in tons per

acre per year, which is the theoretical, long-term amount of soil lost per year due to wind erosion. It is based on the assumption that the soil is bare, lacks a surface crust, is unsheltered and subject to the weather (Woodruff and Siddoway, 1965). Nine WEGs were obtained, which in order of progressively less erodibility, were designated with the indexes 1, 2, 3, 4, 4L, 5, 6, 7, and 8. Digital soil data were not available for the Ciudad Juárez area. Soils there, however, can be generally classified as regosols; these are weakly developed soils of fine-grained unconsolidated materials with a high potential for wind erosion.

Land use and land cover information at the 1:250 000 scale was obtained from the US Geological Survey (USGS) website for the US sites (USGS, 2000). Topologically Integrated Geographic Encoding and Referencing (TIGER) 1995 line files provided information on road and railroad coverage in the study area (USCB, 1995). Political boundaries were obtained as 1:100 000 USGS Digital Line Graph (DLG) files (USGS, 1990). A Global Positioning System was used to obtain the

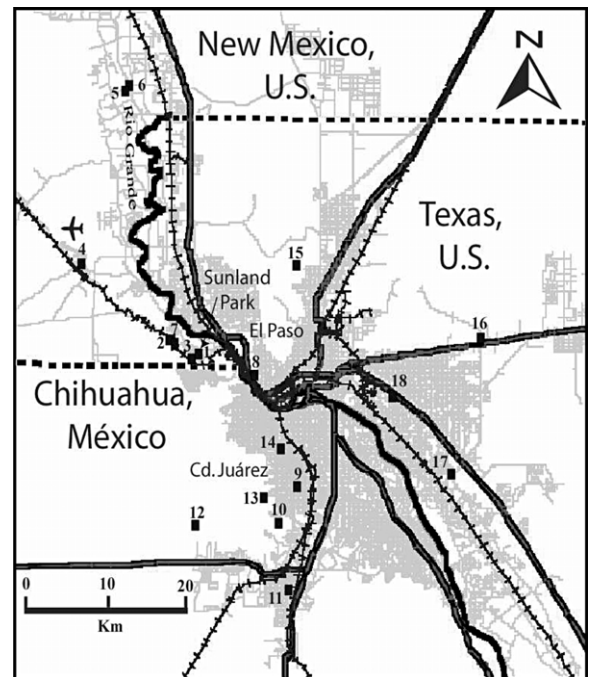


Fig. 3. Sampling site locations.

Table 1
Results of the GIS overlay analysis and sampling site characteristics

Site	State	Latitude (N)	Longitude (W)	WEG ^a	Lithologic Unit ^b	Soil Type ^c	Site description
1	NM	31.47°	106.34°	2	Qalr	PBW	Open field off Anapra Rd. south of Sunland Park ~0.3 miles northeast of Mexican border.
2	NM	31.48°	106.35°	2	Qalr	PBW	Open field ~0.5 mile northeast of Camino Real Landfill southwest of Sunland Park.
4	NM	31.52°	106.42°	3	Qalr	WPC	Open field southwest of Weather Service Office at Santa Teresa Airport, N.M.
5	NM	32.01°	106.38°	4L	Qws	GAH	Plowed agricultural field located west of Anthony, N. M.
6	NM	32.02°	106.38°	4L	Qws	GAH	Dirt road north of O'Hara Rd less than a mile east of Site 5 in agricultural area.
7	NM	31.47°	106.35°	2	Qalr	PBW	Dirt road between Camino Real Landfill and subdivision to its northeast.
8	TX	31.46°	106.30°	8	Qalr	DCN	Hill ~100 ft north of parking lot off Sun Bowl Dr. on UTEP campus.
9	CHIH	31.69°	106.46°	N/A ^d	N/A	N/A	Brick kiln area of Ciudad. Juárez. Sample taken between wall and dirt road to the north.
10	CHIH	31.66°	106.48°	N/A	N/A	N/A	Area southeast of large cement plant
11	CHIH	31.59°	106.46°	N/A	N/A	N/A	Edge of junkyard south of large mound of calcium sulfate at Nor-Fluor plant
12	CHIH	31.64°	106.57°	N/A	N/A	N/A	Open field southwest of large rock quarry
13	CHIH	31.67°	106.48°	N/A	N/A	N/A	Corner of fenced parking lot near dichotomous air sampler.
14	CHIH	31.70°	106.48°	N/A	N/A	N/A	Area immediately southwest of steel mill
15	TX	31.82°	106.47°	8	Qao	RO	Vacant lot just east of large quarry on McKellington Canyon Road in El Paso.
16	TX	31.80°	106.27°	2	Qws	HWB	Open field near intersection of Montana Av. and state highway 375 in east El Paso.
17	TX	31.69°	106.30°	4L	Qao	HGG	Open field near intersection of North Loop Rd. and state highway 375 in southeast El Paso.
18	TX	31.77°	106.39°	2	Qao	BBP	Vacant lot in industrial area containing Phelps Dodge copper plant and Chevron refinery.

Note: ^aThe Wind Erodibility Group (WEG) designates, in order of decreasing number, the long-term amount of soil lost per year due to wind erosion. ^bLithologic unit, ^cSoil type are the geologic unit and type of soil defined in the text, ^dN/A: Not available.

latitude/longitude coordinates for Sites 13, and Sites 9–18. Data for Site 3, however, were not complete and consequently not considered in the

study. The original global positioning system failed after the first two sampling sites and a replacement was not available until the next day. The coordi-

nates of Sites 4–8, therefore were estimated from their street locations.

The first five columns of Table 1 summarize the results of a Geographic Information System (GIS) analysis that was produced using the Arc/Info and ArcView™, version 3.1 (ESRI Inc., 2000) software. The GIS study incorporated all the above data into a common projection (UTM Zone 13, NAD83) to create an overlay of maps to select sites that were representative of the different land uses and soil types in the US.

Additionally, information related to lithologic units and soil types was included for exploring possible associations between data and geologic units, and data and soil types. Three lithologic units covered the sites according to the information taken from Barnes (1993): (1) Young Quaternary alluvium along the Rio Grande (Qalr); (2) Old Quaternary deposits (Qao); and (3) Windblown sand (Qws). Eight soil types were originally considered: (1) Bluepoint-Badland-Pajarito (BBP); (2) DelNorte-Canutio-Nickel (DCN); (3) Glendale-Armijo-Harkey (GAH); (4) Harkey-Glendale-Gila (HGG); (5) Hueco-Wink-Bluepoint (HWB); (6) Pintura-Bluepoint-Wink (PBW); (7) Rock Outcrop (RO); and (8) Wink-Pintura Complex (WPC). For practical purposes, however, the soil for Sites 16 and 18 was considered as PBW type and for Site 17 as GAH type.

The location, related lithologic units and soil types, and a brief description for each site are summarized in Table 1. Lithologic units and soil classification information were not available for the Ciudad Juárez sites.

2.2. Sample collection

One of the sampling sites was a paved road, two were unpaved roads, and the rest were fields, lots, or road shoulders as far away from the road as practical. All three road sites were in the US. One soil sample was collected at each of the six Mexican sites and at the paved road site in the US. Three samples were collected at each of the other eleven sites in the US.

Samples from the road sites were collected by sweeping the loose material on the surface into a clean dustpan with brooms. New brooms were

used and the dustpan was washed with deionized water at each new road site to avoid contaminating samples with material collected at other locations. At the other locations, loose material on a 25 by 25-cm surface was collected with a plastic scoop to a maximum depth of 2 cm to obtain about a liter of soil. At one Ciudad Juárez site where the soil was very hard, four 25 by 25-cm grids were needed to obtain the sample. A square metal frame was used to outline the surface area, and as the soil or loose material was collected, care was taken to prevent contamination of the samples. The scoop and frame were washed with deionized water between sites and disposable plastic gloves were worn by the persons collecting the soils to minimize contamination.

2.3. Sample preparation and analysis

The foreign soil samples were shipped to the Carlsbad Environmental Monitoring and Research Center (CEMRC) of New Mexico State University (NMSU) from Ciudad Juárez on the same day they were collected. This was done to comply with USDA regulations for handling foreign samples. The samples collected in Texas and New Mexico were taken to the Physical Science Laboratory of NMSU. Subsamples of these were shipped to the Lovelace Respiratory Research Institute in Albuquerque, New Mexico where they were fractionated by size using a 2-stage process.

First, the samples were placed into a 6-stage sieve stack, and a coarse separation was performed using wire mesh sieves with cut sizes of 250, 150, 75, 53, 38, and 20 μm . The apparatus used for this first separation step consisted of a Gilson automatic sieve shaker (Gilson Screen Co., Malinta, OH) with a 6-stage sieve stack and a collection pan. All of the sieves were US Standard Testing Sieves and meet ASTM E-11 specifications. Each soil sample was sieved for 15 min and the contents of each sieve were placed into plastic bags, which were then sealed, weighed, and labeled.

In the second separation step, the material that accumulated in the collection pan after the last sieve was recovered and placed into a DeVilbiss Powder Blower (DeVilbiss Health Care Division,

Somerset, PA) for further size separation. The powder blower uses compressed air to create a vortex in the reservoir of the blower and disperse the powder placed in it. The powder blower was pulsed with filtered compressed air to aerosolize the soil samples into a 5-stage cyclone train.

An In-Tox Products 5-Stage Cyclone Train (In-Tox Products, Albuquerque, NM) was used to separate the aerosolized powder using centrifugal forces that are set by the flow conditions. The cyclone train was run at 10 l min^{-1} for all of the separations with five cut-points produced at 7.93, 3.36, 2.49, 1.40, and $0.82 \mu\text{m}$. The contents of each cyclone collection cup were placed into a separate plastic bag or small vial, and these were sealed, weighed, and labeled.

The eleven size-fractionated samples were shipped to CEMRC where 0.1-g aliquots were digested in an acid cocktail (HNO_3 , HCl , and HF) using a microwave system and procedures based on EPA Method 3052. For the soil digestions, 5 ml H_2O , 7 ml HNO_3 , 3 ml HCl , 5 ml HF , and 1 ml H_2O_2 were added to individual Teflon[®] microwave digestion vials that contained 0.1 g of the samples. The vessels were sealed and processed at $180 \text{ }^\circ\text{C}$ in a microwave digestion unit (Model Ethos 900, Milestone Inc.) for 30 min. The samples were then cooled and diluted before analysis. Analyses were performed by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin–Elmer Elan 6000 instrument (Perkin–Elmer Corporation, 761 Main Avenue Norwalk, CT) and following EPA Method 200.8. Matrix matching was used in the preparation of calibration standards for the elemental analyses, and internal standards were used to minimize interferences caused by sample introduction system. This analytical scheme can provide data for up to ~ 40 elements, and the lower limits of quantization are typically in the 1 to 100 ppb range. Typically, the instrument precision is $\pm 1\text{--}5\%$, method precision is $\pm 10\text{--}20\%$, and accuracy is $\pm 10\text{--}20\%$.

A second set of aliquots was extracted with water and analyzed by ion chromatography (IC) also at CEMRC. The aqueous extracts were prepared by weighing 0.1 g of soil into a centrifuge tube, adding 10 ml of ultrapure water, and rotating the mixture on a variable speed rotator. The liquid

extract was then filtered with a syringe filter prior to analysis. The aqueous extracts of the soils were analyzed using a Dionex 500 chromatography system (Dionex Corp., Sunnyvale, CA) with chemical suppression and conductivity detection. The analytes for the IC analyses were fluoride, chloride, nitrate, phosphate, sulfate, lithium, sodium, ammonium, potassium, magnesium, and calcium.

3. Results

3.1. Database

For each of the 18 soil samples, a total of 40 chemical elements concentrations in ppm were obtained for the bulk and the eleven size-separated fractions. The initial focus of the chemical analyses was on elements classified as hazardous air pollutants, including As, Be, Cd, Co, Cr, Hg, Mn, Ni, Pb, Sb, and Se. Of these, the Hg and Se data were dropped from the database because they had very few values above the detection limit. In addition, data for another group of elements (Ag, Al, Ba, Ca, Cu, K, Mo, Na, and Zn) were retained in the database because that information was expected to be useful for source attribution studies.

Chemical concentrations in the soil were characterized for 11 size categories. Table 2 shows the breakdown of chemicals in the fine soil ($< 2.5 \mu\text{m}$). Fine soil data for several sites were not included in this table because insufficient mass was available for analyses. For the valid samples, a large portion of the total mass is classified as ‘others’. This is to be expected because the majority of mass exists in various forms of the geologic/crustal materials (e.g. Al_2O_3 , SiO_2 , CaO , FeO / Fe_2O_3 , and TiO_2) such that the mass in oxidized form is not accounted for in the ICP-MS analysis. Alternatively, one could estimate mineral mass by multiplying the observed Al concentration by 12.4 (based on the fact that the Earth’s upper crust contains 8.04% Al according to Taylor and McLennan, 1995) and not including the data for Si, Ca, etc. No adjustment for other mineral mass was made in this study.

Table 2
Chemical concentrations for the fine size fraction in percentage of total mass

Compound	Site							
	1	5	6	8	15	16	17	18
Ag	1.53E-03	8.21E-05	8.60E-05	1.24E-02	1.51E-03	2.72E-04	8.43E-05	3.66E-04
Al	1.37E+01	7.60E+00	8.90E+00	6.17E+00	1.72E+00	1.11E+01	4.07E+00	4.00E+00
As	2.22E-02	2.84E-03	3.51E-03	2.37E-01	3.64E-03	1.77E-03	1.57E-03	2.02E-03
Ba	1.42E-01	5.34E-02	5.94E-02	6.45E-02	5.96E-02	7.08E-02	5.18E-02	5.62E-02
Be	1.47E-02	1.52E-03	1.70E-03	6.20E-04	2.24E-03	8.35E-03	9.56E-04	7.64E-04
Ca	1.26E+01	5.16E+00	5.00E+00	3.75E+00	9.54E+00	6.34E+00	5.70E+00	6.88E+00
Cd	4.70E-03	1.09E-04	7.99E-05	3.36E-02	1.80E-03	5.64E-04	1.53E-04	2.89E-04
Ce	2.37E-02	9.30E-03	1.01E-02	7.20E-03	5.90E-03	1.34E-02	6.78E-03	7.80E-03
Co	2.19E-02	5.89E-03	5.08E-03	7.64E-03	1.71E-02	8.43E-03	6.12E-03	9.98E-03
Cr	1.53E-03	4.90E-03	4.52E-03	6.14E-03	5.75E-03	8.81E-03	3.83E-03	4.47E-03
Cu	1.10E+00	5.00E-02	1.10E-01	1.49E+00	4.00E-02	9.30E-01	4.00E-02	1.50E-01
Dy	1.51E-03	6.09E-04	6.50E-04	4.70E-04	3.92E-06	8.35E-04	8.65E-05	2.01E-04
Er	8.92E-04	3.43E-04	3.72E-04	2.65E-04	2.63E-06	4.89E-04	4.99E-05	1.19E-04
Eu	4.61E-04	1.95E-04	2.06E-04	1.67E-04	7.25E-05	2.33E-04	5.38E-05	7.74E-05
Fe	8.13E+00	3.63E+00	3.86E+00	4.42E+00	2.59E+00	5.94E+00	3.04E+00	3.16E+00
Gd	3.11E-03	1.06E-03	1.12E-03	9.79E-04	2.55E-04	1.52E-03	3.54E-04	6.04E-04
K	5.32E+00	2.14E+00	1.74E+00	1.49E+00	1.79E+00	3.35E+00	1.90E+00	1.59E+00
La	1.09E-02	4.32E-03	4.89E-03	3.47E-03	2.56E-04	6.03E-03	7.14E-04	1.66E-03
Li	1.23E-02	7.99E-03	7.48E-03	4.68E-03	5.99E-03	8.17E-03	8.77E-03	7.61E-03
Mg	3.63E+00	1.49E+00	1.63E+00	1.49E+00	1.77E+00	2.52E+00	1.49E+00	1.55E+00
Mn	3.00E-01	9.00E-02	9.00E-02	1.49E+00	9.00E-02	1.40E-01	9.00E-02	1.10E-01
Mo	1.24E-03	1.87E-04	2.42E-04	1.37E-02	2.23E-03	6.22E-04	1.56E-04	2.10E-04
Na	1.05E+00	4.00E-01	5.50E-01	4.40E-01	9.90E-01	4.40E-01	2.00E-02	3.60E-01
Nd	9.75E-03	3.93E-03	4.22E-03	3.11E-03	3.60E-05	5.29E-03	5.75E-04	1.25E-03
Ni	1.28E-02	3.41E-03	1.01E-02	6.89E-03	4.54E-03	1.45E-02	2.83E-03	5.27E-03
Pb	5.08E-01	8.78E-03	7.84E-03	1.75E+00	2.62E-02	4.73E-02	7.58E-03	1.85E-02
Pr	2.62E-03	1.07E-03	1.16E-03	8.51E-04	2.98E-05	1.48E-03	1.67E-04	3.63E-04
Sb	3.91E-03	1.55E-04	1.67E-04	3.96E-02	2.08E-03	4.88E-04	1.33E-04	3.11E-03
Sc	1.30E-02	5.22E-03	6.07E-03	4.17E-03	4.34E-03	8.13E-03	4.33E-03	4.95E-03
Sm	2.08E-03	8.24E-04	8.80E-04	6.49E-04	5.33E-05	1.10E-03	1.49E-04	2.81E-04
Sr	8.00E-02	3.00E-02	4.00E-02	2.00E-02	3.00E-02	4.00E-02	4.00E-02	4.00E-02
Th	3.53E-03	1.53E-03	1.62E-03	1.16E-03	1.69E-05	2.15E-03	1.88E-04	3.81E-04
Ti	8.30E-01	3.80E-01	4.60E-01	3.40E-01	2.50E-01	5.20E-01	3.20E-01	3.50E-01
Tl	1.00E-03	9.62E-05	9.76E-05	3.29E-03	1.56E-03	2.23E-04	8.35E-05	1.03E-04
U	1.08E-03	4.26E-04	5.09E-04	3.81E-04	1.92E-03	4.58E-04	3.91E-04	4.63E-04
V	1.25E-02	8.10E-03	1.23E-02	4.34E-03	6.76E-03	8.67E-03	6.24E-03	8.10E-03
Zn	7.80E-01	3.00E-02	6.00E-02	5.10E-01	5.00E-02	4.30E-01	2.00E-02	1.00E-01
Chloride	0.00E+00	1.26E-02	0.00E+00	2.55E-03	1.47E-03	0.00E+00	5.48E-02	3.48E-03
Nitrate	0.00E+00	1.66E-02	0.00E+00	1.07E-02	5.61E-03	0.00E+00	2.88E-02	4.89E-03
Sulfate	0.00E+00	5.36E-02	0.00E+00	3.03E-02	5.24E-03	0.00E+00	2.96E-01	1.34E-02
Phosphate	0.00E+00	0.00E+00	0.00E+00	1.43E-03	3.78E-03	0.00E+00	1.46E-03	0.00E+00
Fluoride	0.00E+00	9.57E-04	0.00E+00	9.00E-04	5.70E-04	0.00E+00	9.15E-04	8.32E-04
Others	5.17E+01	7.88E+01	7.74E+01	7.61E+01	8.10E+01	6.80E+01	8.28E+01	8.16E+01

3.2. Relationships among elemental concentrations and sites

The mean (\bar{x}) and standard deviation (s) for each bulk element concentration across all sam-

pling sites were calculated. The corresponding standardized values (Z) were calculated according to the formula

$$Z = (\text{bulk element concentration} - \bar{x})/s.$$

Table 3
Main characteristics of standardized bulk elements concentrations

Element	Highest Z		Range of Z values for lithologic units*			Highest Z _{soil}	
	Value	Site	Qalr	Qao	Qws	Value	Soil type
Ag	3.2	8	3.5	0.0	0.0	3.2	DCN
Al	1.4	1	1.1	2.1	2.1	2.3	RO
As	3.2	8	3.5	0.0	0.1	3.2	DCN
Ba	1.5	1	1.5	1.0	0.9	1.7	RO
Be	2.2	6	0.8	0.6	4.1	1.1	GAH
Ca	3.0	15	0.6	3.1	0.5	3.0	RO
Cd	3.2	8	3.5	0.0	0.0	3.2	DCN
Co	2.2	15	2.3	2.2	1.3	2.2	RO
Cr	1.7	6	1.7	0.7	2.8	1.2	GAH
Cu	3.2	8	3.5	0.3	0.0	3.2	DCN
K	1.7	1	2.1	0.8	1.4	1.7	WPC
Mn	1.6	8	2.9	0.7	2.7	1.6	DCN
Mo	3.2	8	3.5	0.1	0.1	3.2	DCN
Na	2.5	8	2.5	0.5	0.9	2.5	DCN
Ni	1.6	8	2.9	0.9	2.3	1.7	DCN
Pb	3.2	8	3.5	0.1	0.0	3.2	DCN
Sb	3.2	8	3.5	0.0	0.0	3.2	DCN
Zn	3.2	8	3.5	0.2	0.1	3.2	DCN

* Lithologic units and soil types are defined in the text.

A high Z value for a given element at one particular site could imply the presence of a significant source for the element at that site. The results, which are presented in the first two columns of Table 3, indicate that: (1) Ag, As, Cd, Cu, Mn, Mo, Na, Ni, Pb, Sb, and Zn had their maximum values at Site 8, which is a hill near UTEP campus, and it is the closest sampling site to the ASARCO smelter; (2) the highest values for Al, Ba, and K occurred at Site 1, which is an open field located in New Mexico; (3) the peak values for Ca and Co occurred at Site 15, which is a quarry located at El Paso; and (4) Be and Cr showed their maximum values at Site 6 that is located in the proximity of an agricultural area (Table 1 and Fig. 3).

3.3. Relationships between elemental concentrations and lithologic units

For each element, a range value was calculated, and these were defined as the difference between the maximum and minimum Z values for the

element across all sampling sites belonging to the same lithologic unit. Additionally, the range values for each element were compared among lithologic units to investigate possible associations between the elemental concentrations and lithologic units. That is, a constant pattern of range values across all lithologic units would suggest the absence of strong natural or anthropogenic influences, and a high range value for one particular geologic unit would suggest significant impacts from natural or anthropogenic sources.

The results of this analysis (Table 3) can be summarized as follows: (1) The range values of Ag, As, Cd, Cu, K, Mo, Na, Pb, Sb, and Zn across all geologic units were variable and had their highest values in the soil samples belonging to the Qalr lithologic unit, suggesting natural or anthropogenic impacts; (2) Al, Ba, Co, Mn, and Ni had nearly the same range value in two of the sample lithologic units, suggesting that one or more sources dominate these elements; (3) Ca had its maximum range value in the Qao unit, possibly indicating a significant geologic source for this element; and (4) Be and Cr showed their maximum range values on sites belonging to the Qws geologic unit, indicating perhaps a common source for both elements.

3.4. Relationships between elemental concentrations and soil types

For each element, the averages of its Z values across all sampling sites having the same type of soil (Z_{soil}) were obtained and compared among the different soil types. A high Z_{soil} value in one particular soil type would indicate, for example, the existence of a significant soil source related to the element.

Results are summarized in the last two columns of Table 3, which show that: (1) The highest Z_{soil} values for each one of the elements Ag, As, Cd, Cu, Mn, Mo, Na, Ni, Pb, Sb, Zn were produced on the DCN soil type suggesting a common source for all these elements associated to this type of soil; (2) Al, Ba, Ca, and Co were mainly associated with the RO soil type indicating perhaps the same source for these elements; (3) K was related

to the WPC soil type; and (4) Be and Cr had their highest average values on the GAH soil type.

4. Statistical analyses

Environmental data are often multivariate, complex, redundant, and not directly interpretable (Gauch, 1982), and as such they are especially amenable to interpretation using a variety of different approaches. The soil data in this study were further analyzed under a multi-element scheme using multivariate methods and enrichment factor analysis. The soil data were first analyzed using three multivariate methods to evaluate potential sources of surface soil, and then they were subjected to the enrichment factor analysis to semi-quantitatively characterize the levels of enrichment in the soil.

4.1. Multivariate methods

Three multivariate methods: (1) cluster analysis (CA); (2) ordination analysis; and (3) direct gradient analysis, as classified by Jongman et al. (1985), were employed in the soil data analysis. For our study, CA and principal components analysis (PCA), a form of ordination analysis, were applied to the soil data using Statistica™, version 5.0 (Statsoft Inc., 1995) software. Canoco™, version 4.5 (Canoco, 1998) software was used for performing redundancy analysis (RDA), which is a type of direct gradient analysis.

The goal of CA is to identify ‘natural’ groupings among a collection of heterogeneous sampling observations. Objects that belong to the same cluster are similar with respect to a predetermined selection criterion. The resulting clusters exhibit high internal (within-cluster) homogeneity and high external (between-cluster) heterogeneity (Grimm and Yarnold, 2000).

Ordination analyses are generally applied to unimodal data. Among the available ordination methods, PCA is used to reduce the number of original variables into a set of principal components, which are linear combinations of the original variables; these are constructed in such way that in most cases, the first few principal components

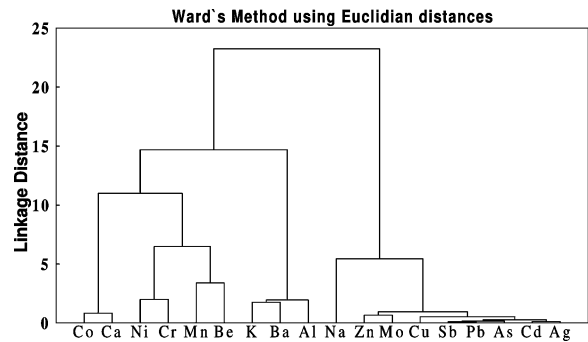


Fig. 4. Dendrogram of the standardized bulk element concentrations.

account for most of the total variance (Dunteman, 1984).

Direct gradient analysis is a generalized form of regression analysis, in which the data distribution is assumed linear, and a set of dependent variables is coupled with a set of independent variables (explanatory or environmental variables). RDA, for example, is a direct gradient technique, which is the canonical form of PCA. The RDA algorithm selects the best linear combination of environmental variables that minimizes the total residual sum of squares (Ter Braak and Prentice, 1986).

4.1.1. Cluster analysis

A CA was applied to the standardized bulk concentration data using Ward's method, with Euclidian distances as the criterion for forming clusters of elements. Ward's method uses an analysis of variance approach to evaluate the distances among the clusters of elements to determine when two of them are sufficiently similar to be linked. In general, this form of CA is regarded as very efficient, although it tends to create small clusters. Distances were calculated as the geometric distances between points representing the clusters in the multidimensional space generated by the clustering algorithm. Fig. 4 displays five clusters produced using this approach: (1) Ca–Co; (2) Be–Cr–Mn–Ni; (3) Al–Ba–K; (4) Na; and (5) Ag–As–Cd–Cu–Mo–Pb–Sb–Zn. It is observed, however, that clusters 1, 2 and 3 group together at a higher level implying perhaps a common source for these groups.

4.1.2. Principal components analysis

A PCA with VARIMAX normalized rotation was applied to the original bulk concentration data. The VARIMAX rotation is the most commonly used rotational strategy; it maximizes the variances of the squared normalized factor loadings across variables for each factor. The goal of rotational algorithms is to obtain a clearer pattern of loadings, that is, factors that are clearly marked by high loadings for some variables and low loadings for others. In this respect, loadings >0.71 are typically regarded as excellent and <0.32 very poor (Grimm and Yarnold, 2000). In our analysis, all principal factors with eigenvalues >1.0 were retained, as suggested by the Kaiser criterion (Kaiser, 1960).

The PCA produced three factors that explained 91% of the total variance in the data. The first factor was composed of Ag, As, Cd, Cu, Mo, Pb, Sb, Zn, and Na, and it explained 51% of the data variance. These elements had loadings of 0.99, except for Zn and Na, which had values of 0.98 and 0.70, respectively. The second factor extracted explained 28% of the variance, and it was made up of Al, Ba, Be, K, Ca, and Co with respective loadings of 0.93, 0.93, 0.71, 0.96, -0.92 and -0.96 . The third factor was formed from Cr, Mn, and Ni with positive loadings of 0.90, 0.78, and 0.84, respectively.

4.1.3. Redundancy analysis

RDA was applied to the original and logarithmically transformed size-fractionated soil data using the WEG, the distance to the ASARCO smelter (indicated as SMELTER in Fig. 5), and the size-cut of the soil fraction (indicated as SIZE in Fig. 5) as preliminary explanatory variables. The distance between the sampling site and the ASARCO smelter (in kilometers) was evaluated because several studies (Landrigan et al., 1975; Rosenblum et al., 1975; Ordóñez et al., 1976; Landrigan and Baker, 1981; Dydek, 1990; Barnes, 1993; Ndame, 1993) conducted on metals in the PdN region, have indicated the potential for high heavy metals concentrations close to the smelter. The size fractions of the soils (0.82, 1.40, 2.49, 3.36, 7.93, 20, 38, 53, 75, 150, and >250 μm) were taken as the

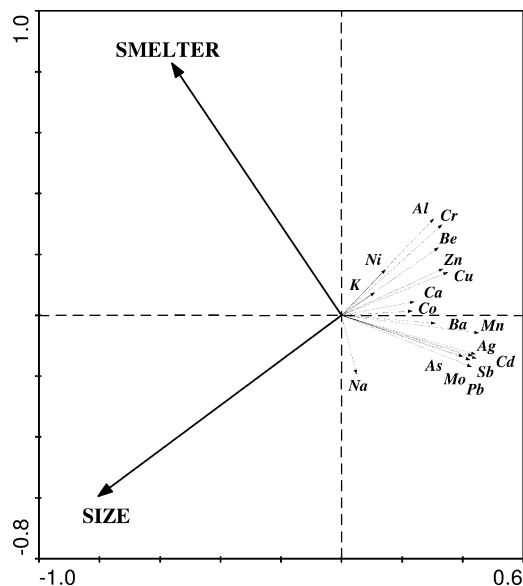


Fig. 5. RDA of the logarithmically transformed fractioned element concentrations for all sites.

third explanatory variable to investigate soil grain-size effects.

The RDA showed that the most readily interpretable results were obtained for the logarithmically transformed data with SMELTER and SIZE as independent variables. The WEG variable was not a significant explanatory variable in any case. Results are graphically displayed as a biplot graph (Fig. 5); this is an ordination diagram showing the concentrations of the elements and the environmental variables as arrows that point in the direction of steepest increase of values for the corresponding variables. The angles between arrows indicate correlations or covariances between the associated variables.

The main results of the RDA can be summarized as follows: First, sodium was positively correlated to SIZE indicating that its highest concentration occurs in the largest soil size fraction. All the other elements, especially Al, Be, Cr, Cu, K, Ni, and Zn had a negative correlation to SIZE indicating that their highest concentrations occur in the smaller sized particles. Second, Al, Be, Cr, K, and Ni arrows were approximately orthogonal to SMELTER vector, which means that they are not

correlated with the distance to the smelter. Finally, and in contrast to the preceding group, Ag, As, Ba, Ca, Co, Cd, Cu, Mo, Mn, Na, Pb, Sb, and Zn were anti-correlated with SMELTER, implying that their concentrations decrease as the distance between the sampling site and smelter increases.

4.2. Enrichment factor analysis

A comparison between the observed elemental concentrations in the soil and the composition of Earth's upper continental crust was made to determine the magnitude and patterns of soil enrichments. Enrichment factors (EFs) calculated relative to the composition of the Earth's crust have been commonly used in aerosol studies (Rahn, 1976; Cyrus et al., 2003), and these are a simple, semi-quantitative, way of determining whether the elemental concentrations in the samples of interest are consistent with or enriched relative to what one would expect from the amount of crustal/mineral matter in the sample. EFs were calculated using the formula

$$EF = \frac{\left[\frac{\text{element}}{\text{reference element}} \right]_{\text{sample}}}{\left[\frac{\text{element}}{\text{reference element}} \right]_{\text{crust}}}$$

where element refers to the concentration of the element of interest and reference element refers to the concentration of crustal rock, most commonly Al or Si. Here we used Al as the reference element and the compilation of Taylor and McLennan (1995) to calculate EFs.

In general, one would expect only those elements dominated by a crustal source to have EFs approaching unity. This is typically the case for elements such as Si, Ca, and Fe for example, that make up a significant fraction of the mineral matter, and it is also true for other elements that may exist in low concentrations in the mineral matter but have not been significantly impacted by other sources (either natural or anthropogenic). The concentrations of other elements (Pb and As, for example) in crustal material may be low or high in an absolute sense, but the important point

Table 4

Highest enrichment factors with correspondent sites in parenthesis (Al as reference element)

Element	Size fraction		
	Bulk	Coarse (2.49–7.93 μm)	Fine (<2.5 μm)
Ag	672 (8)	3107 (8)	3594 (8)
As	450 (8)	1672 (8)	2231 (8)
Ba	11 (10)	35 (13)	5 (15)
Be	6 (10)	59 (4)	151 (4)
Ca	245 (10)	159 (13)	14 (15)
Cd	863 (8)	3545 (8)	4980 (8)
Co	258 (10)	386 (13)	75 (15)
Cr	13 (10)	65 (13)	8 (15)
Cu	272 (8)	2241 (4)	2666 (4)
K	9 (10)	13 (13)	3 (15)
Mn	10 (10)	36 (8)	32 (8)
Mo	32 (8)	152 (8)	127 (8)
Na	6 (10)	7 (13)	2 (15)
Ni	23 (10)	61 (13)	156 (4)
Pb	193 (8)	887 (8)	1208 (8)
Sb	793 (8)	3159 (8)	2730 (8)
Zn	34 (13)	369 (4)	482 (4)

is that they are low compared with the contributions from other sources, and that is why their EFs are much higher than one. Very commonly, these enrichments are due to material from pollution sources.

It is possible that an EF for a given element could be less than unity, and this could occur in one of two ways: First, an EF < 1 could occur if there were a non-crustal source affecting the sample for the reference element (typically Al or Si) used in the denominators (i.e. the X-to-reference element ratios) in the EFs. Second, an EF could be less than unity if the actual source of the crustal material were depleted in element X relative to average crustal material (which is used to define the X-to-reference element ratio in the denominator of the EF). But in either case, the effect would likely be quite small.

EFs for PdN fugitive dust source materials were calculated separately for fine and coarse particles, with sizes of <2.49 μm and 2.49 μm to 7.93 μm, respectively. The results, summarized in Table 4, show that Ag, As, Cd, Cu, Pb, and Zn had the

same general patterns in EFs, with increasing enrichments from bulk to coarse to fine particles. It was observed also that the highest EFs for these elements occurred most frequently at the site (Site 8) near the UTEP campus which is climatologically downwind of ASARCO. In the fine and coarse fractions all of these elements had EFs higher than 1000, except for Zn, which showed EFs < 500.

A second group of elements Ba, K, Ca, Co, and Na showed the same general pattern of enrichments, but these were different from the first group. The highest EFs for this group always occurred at Site 10 (near a cement plant) for the bulk material, at Site 13 (near a parking lot) for the coarse size fraction, and at Site 15 (a vacant lot near a quarry) for the fine fraction. Ba, K, and Na presented moderate EFs (<35), whereas Ca and Co high EFs (approx. 190 on average). Be and Ni were most frequently enriched at Site 4 (an open field near an airport) on the fine and coarse sizes with the same EFs of 150 and 60, respectively, while Cr and Mn had their highest EFs on the coarse sized particles with values of 65 and 36, respectively.

The EFs values varied with respect to the lithologic units and soil types. The main results concerning the geologic units were that in all size fractions the highest and lowest EFs for Ag, As, Cd, Cu, Mo, Pb, Sb, and Zn occurred on the Qalr and Qws lithologic units, respectively. Correspondingly, Ba, Ca, Co, and K had their highest and lowest EFs on the Qao and Qws geologic units. The maximum and minimum EFs for Cr and Ni occurred on the Qao and Qalr lithologic units. Implications of these findings are discussed below.

The distribution of EFs as functions of soil types showed that the highest EFs occurred on the DCN soil type for all the elements in the fine size fraction, except for Ba, Cr, K, Na, and Ni. The coarse sized particles of Ag, As, Cd, Mn, Mo, Pb, and Sb had their highest EFs on the DCN soil type, whereas for Ba, Ca, Co, Cr, K, and Ni the highest occurred on the RO soil type. All elements in the bulk material had their highest EFs occurred on the GAH soil type, except Ba, Ca, Cr, and K which had them on the WPC soil type.

5. Discussion

Four sets of elements consistently appeared in the applied analyses; these are (1) Ag–As–Cd–Cu–Mo–Pb–Sb–Zn; (2) Na; (3) Al–Ba–K–Ca–Co; and (4) Be–Cr–Mn–Ni. Results for the first group of elements, suggest that they have a common source associated with the Qalr geologic unit and the DCN soil type. Superimposed on the geological signal, however, are signals that appear to be from anthropogenic sources. In particular, it is important to note that the DCN soil association, which in this case is related to Site 8, skirts the Franklin Mountains, encompasses an area occupied by ASARCO and other anthropogenic sources. Site 8, exhibited the highest standardized concentrations of these elements (Table 3), and it is the sampling site closest to the smelter.

The CA and PCA produced practically identical groupings of elements. The combination Ag–As–Cd–Cu–Mo–Pb–Sb–Zn coupled with Na was the first factor extracted by PCA, and it explained 51% of the variance data. In this case, the Na loading (0.70) was not as high as the loadings of the other elements of the group (which were all 0.98). Therefore, Na appears to be only weakly related to the other elements of the group, which implies a quasi-independent behavior for this element; Na is discussed in more detail below.

As, Pb, Cd, Sb, and Cu were identified by Blanchard and Stromberg (1987) as elements associated with smelter. Significantly higher concentrations of these elements were found on copper and lead smelter workers as compared to urban controls (Gerhardsson et al., 1988). These elements could serve as a tracer for lead smelter emissions as they are volatile and associated with small diameter particles in the furnace emissions that can travel significant distances from the source (Kimbrough and Suffet, 1995). The highest enrichment factors for Ag–As–Cd–Cu–Mo–Pb–Sb–Zn were observed in the fine particle fraction at Site 8, suggesting the ASARCO smelter as a possible source. Results of the RDA, showed that each of these elements had a negative correlation to SMELTER, meaning that their concentrations in the soils decrease with distance from the smelter. Additionally, all these elements had a strong neg-

ative correlation with SIZE suggesting an anthropogenic origin for them. All of these results reinforce the identification of ASARCO as a probable source for these elements. In this regard, the elements group Ag–As–Cd–Cu–Mo–Pb–Sb–Zn can be interpreted as a smelter metals group (Barnes, 1993; Ndamo, 1993).

The highest standardized concentration value of Na occurred at Site 8 (Table 3), and the maximum range and highest Z_{soil} values took place in the Qalr lithologic unit and DCN soil type, respectively, (Table 3). Na had a strong negative correlation with SMELTER (Fig. 5). As in the first group of elements discussed, these findings suggest that Na has ASARCO as a possible source. However, the enrichment factor analysis shows that Na had only low enrichment factors in all size fractions (Table 4), which indicates at most modest anthropogenic influences on this element. Additionally, the RDA demonstrated that Na had a positive correlation with SIZE (Fig. 5), which implies that the highest Na concentration values occur on the coarse sized particles. This combination of results suggest that the Na concentrations could be affected by a natural source located close to the smelter, such as soil that has been salinized under salt wind-transport and accumulation.

The next group of elements consisted of Al–Ba–K–Ca–Co. All these elements, except Ca and Co, had their highest standardized concentration values at Site 1, which is an open field, indicating perhaps a crustal origin for these elements (Table 3). Ca and Co exhibited their maximum standardized concentration values at Site 15 located in a vacant lot just to the east of a large quarry in El Paso, strongly suggesting a geological origin for them (Table 3). The distributions of Al, Ba, and Co concentrations indicated that they were not associated to any particular lithologic unit and were in all likelihood from natural geological sources. K and Ca were strongly related to the Qalr and Qao geologic units, respectively, (Table 3). Additionally, Al, Ba, Ca, and Co were associated with the RO soil type located at Site 15 (quarry), which supports a crustal origin for all these elements.

At the first level of classification, the clustering process assigned Ca and Co to one group and Al,

Ba, and K in another group. However, both groups were clustered together in the next clustering level. PCA produced the combination of Al–Ba–Be–K–Ca–Co as the second factor, explaining 28% of the data variance. In this factor, Be had the lowest loading (0.71), implying that it has a lowest affinity for the Al–Ba–K–Ca–Co group. Ba and K showed little or no enrichment relative to Al in the bulk material, consistent with a natural geological source for these elements (Table 4).

Except for Ba, all the elements in the Al–Ba–K–Ca–Co group had a low or null correlation to SMELTER (Fig. 5). However, all of them had strong or moderate negative correlations to SIZE most likely reflecting variations in mineral composition with particle size, especially the influence of large quartz particles. The calculation of EFs supports this hypothesis because each of the five elements in this group had at most a modest EF in the bulk material. This interpretation of the EF calculations is, therefore, consistent with that from the descriptive (Sections 3.2, 3.3 and 3.4) and multivariate analyses (Sections 4.1.1, 4.1.2 and 4.1.3), i.e. that this group of elements is of crustal origin.

The last group composed of Be–Cr–Mn–Ni showed mixed signals. The first sub-group Be–Cr was related to the Qws lithologic unit and GAH soil type through its association to agricultural fields located at Sites 5 and 6 (Table 1). This could indicate either a natural source or an influence of anthropogenic influence related to agricultural practices. Mn and Ni had practically the same range and Z_{soil} values across the lithologic units and soil types (Table 3), which suggest a natural common origin for them. Both elements were mainly associated to the DCN soil type, which also is consistent with a common origin. Furthermore, the clustering of these elements is consistent with the PCA results, which showed the combination Cr–Mn–Ni as the third factor responsible for 12% of the variance in the data. Be and Ni had their highest enrichment factors on the fine soil fraction at Site 4, whereas Cr and Mn on the coarse sized particles at Sites 13 and 8, respectively, (Table 4); these patterns indicate a mixed origin perhaps associated to industrial or natural activities located in the proximity of Sites 4, 13 and 8.

Each one of the elements of the set Be–Cr–Ni exhibited a low or zero correlation to SMELTER and a strong negative correlation to SIZE, indicating an industrial source not related to ASARCO for these elements. The same conclusion can be inferred for Mn, even though had slight negative correlations to SMELTER and SIZE (Fig. 5).

6. Conclusions

The application of multivariate statistical techniques coupled with enrichment factor analysis has proved to be a useful tool for identifying groups of related elements. The inclusion of geological and geographical information facilitated the interpretation of the sources for the obtained four groups of elements.

There appear to be significant impacts from a smelter and a quarry on the composition of potential sources for fugitive dust, with possible minor impacts from agriculture. The materials presumed to be from the smelter were mainly evident in a relatively confined area, near the UTEP campus. Five of the elements evaluated (Al–Ba–K–Ca–Co) were in crustal or near crustal proportions, and other trace elements not specifically evaluated, such as the rare earths would likely exhibit similar patterns. In addition, impacts from quarries on some elements such as Ca and Co are suggested.

Some crustal dust is raised by human activities, so that material can in a sense be considered a pollutant, and more generally some anthropogenic materials, most notably coal fly ash, are chemically similar to natural dust. Thus distinguishing between natural and anthropogenic geological materials is not a simple matter. Fine particles emitted from many of the fugitive dust sources investigated will be enriched with various trace elements. Compared with coarse particles, the fine particle fraction is more likely to remain suspended in the atmosphere long enough to be transported long distances, and fine particles are also the greatest concern from a public health standpoint. Thus, the resuspension of previously deposited chemical contaminants should be recognized as a potentially significant long-term source for air pollutants.

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