

Introduction to the GSC MITE Point Sources project

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Abstract: The Point Sources project of the Geological Survey of Canada's Metals in the Environment Initiative (1997–2002) examined the distribution of metals in various environmental sampling media around three Canadian metal smelters at Rouyn-Noranda (Quebec), Belledune (New Brunswick), and Trail (British Columbia). This bulletin contains eleven papers on the studies made at Rouyn-Noranda and one paper on work at the Belledune smelter.

Regional surveys of snow, soil, lake sediment, peat, and vegetation were used to characterize and understand metal dispersal around the Horne smelter at Rouyn-Noranda. Metals emitted by the Horne smelter are transported by the atmosphere and radially dispersed around this point source. The resulting smelter footprint, i.e. where metal concentrations are significantly higher than ambient background levels, shows exponentially decreasing values with increasing distance from the source in various environmental media (snow, soil, peat, lake sediment, trees). Snow data provide information about metal loading (deposition rates) in winter conditions. The most recent growth of peat hummocks provides independent estimates of metal loading over one year. Loading data (modelled as a function of distance from the smelter) provide estimates of the total tonnage of metal deposited within (and close to) the footprint for comparison with emission data.

The distribution of metals in marine sediments near the Brunswick lead smelter is controlled by both atmospheric and oceanographic processes. The influence of the emissions on metal levels in coastal sediments near Belledune extends at least 20 km from the smelter.

Résumé : Le projet sur les sources ponctuelles, qui s'inscrivait dans le programme des Métaux dans l'environnement (1997-2002) de la Commission géologique du Canada, visait l'étude de la répartition des métaux prélevés dans divers milieux aux environs de trois fonderies canadiennes situées respectivement à Rouyn-Noranda (Québec), à Belledune (Nouveau-Brunswick) et à Trail (Colombie-Britannique). Le présent bulletin comprend onze articles sur des études menées à Rouyn-Noranda et un article sur des travaux de recherche exécutés aux alentours de la fonderie de Belledune.

Des études régionales ont été menées sur la neige, le sol, les sédiments lacustres, la tourbe et la végétation pour connaître et mieux comprendre les caractéristiques de la répartition des métaux aux alentours de la fonderie Horne, à Rouyn-Noranda. Les émissions de métaux de la fonderie Horne sont transportées dans l'atmosphère et dispersées radialement autour de cette source ponctuelle. La zone résultante de concentrations significatives de métaux émis par la fonderie, c'est-à-dire l'endroit où ces concentrations sont significativement supérieures aux concentrations naturelles ou de fond, présente des valeurs qui diminuent exponentiellement en s'éloignant de la fonderie dans divers milieux (neige, sol, tourbe, sédiments lacustres, arbres). Les données sur les échantillons de neige renseignent sur les charges en métaux (taux de dépôt) dans des conditions hivernales. La plus récente croissance des buttes de tourbe permet l'estimation des charges en métaux pour une année donnée. Les données sur les charges (modélisées en fonction de la distance par rapport à la fonderie) permettent d'estimer le tonnage total des métaux déposés à l'intérieur (et à proximité) de la zone de concentrations significatives à des fins de comparaison avec les données sur les émissions.

Près de la fonderie de plomb Brunswick, les métaux sont répartis dans les sédiments marins par des processus atmosphériques et océaniques. Près de Belledune, l'incidence des émissions sur les concentrations de métaux dans les sédiments côtiers peut être observée au moins jusqu'à 20 km de la fonderie.

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INTRODUCTION

The Geological Survey of Canada's five-year Metals in the Environment (GSC MITE) Initiative began in April 1997 and ended in March 2002 (R.G. Garrett, unpub. rept., 2002). A major component of the GSC MITE was the Point Sources project, which was designed to gain an understanding of how metals emitted from smelters affect the surface environment in different ecosystem settings. A principal objective of the project was to characterize the spatio-temporal distribution of smelter-emitted metals in various surficial media around one or more of Canada's smelters. The intended outcome of the project was to bring a geoscience perspective to Canada's policies on metal smelter emissions and provide information that could support risk assessments of the effects of metal emissions on ecosystem and human health.

In order to achieve this outcome, the project addressed the following key questions, answers to which are provided in Appendix A:

1. What are the shape and size of smelter 'footprints', as seen in regional geochemical surveys of soil, snow, water, sediment, and vegetation?
2. Can the metals present in samples collected at various distances from a smelter be apportioned into 'anthropogenic' (i.e. emitted from a smelter or other human sources) and 'natural' sources?
3. What does the study of the geological environment reveal about the chemical and mineralogical forms of metals in surficial media around smelters, and can the availability of smelter-emitted metals to biota be determined?
4. What can we learn about the history of atmospheric metal deposition from natural archives such as lake sediments, tree rings, and peat deposits in the vicinity of smelters?
5. Can we determine how far smelter emissions travel in the atmosphere from the study of surficial materials?
6. Can a predictive model be constructed that can be used to estimate the rate of deposition of metals from smelters as a function of wind direction and distance from source, on the basis of evidence from surficial environmental media?

In parallel with the GSC MITE Initiative, a government-university program — the Metals in the Environment Research Network (MITE-RN) — was established in July 1998, initially as a five-year program (1998–2003), and was managed by the Canadian Network of Toxicology Centres (CNTC), with its head office at the University of Guelph, Ontario. The MITE-RN's aims were to understand the sources of metals in the environment, how metals move and are transformed in the environment, how metals can affect ecosystem health, and the nature and extent of the ecosystem risk posed by smelter emissions. The MITE-RN projects were subdivided into three groups: sources, processes and impacts. Several MITE-RN projects involved studies in the Rouyn-Noranda area and complemented the GSC MITE Point Sources project, in particular those dealing with the sampling, analysis, and modelling of airborne emissions

by plume studies (work led by Environment Canada's Meteorological Service of Canada). Some GSC MITE activities were closely linked to MITE-RN, with GSC scientists leading and collaborating on MITE-RN projects.

Out of the 15 base-metal smelters and refineries in Canada (Table 1, Fig. 1), four smelters were considered for detailed study by GSC MITE: the Teck Cominco Limited lead-zinc smelter at Trail, British Columbia; the Hudson Bay Mining & Smelting Co. copper smelter at Flin Flon, Manitoba; the Noranda, Inc. copper smelter at Rouyn-Noranda, Quebec; and the Noranda, Inc. lead smelter at Belledune, New Brunswick. Some characteristics of these smelters are summarized in Table 2. Prior to the start of GSC MITE, Henderson et al. (1998) and McMartin et al. (1999) studied the distribution of metals in the humus horizon of soils around Flin Flon. They demonstrated that a large anomaly was present in this sample medium around the smelter. Bonham-Carter and McMartin (1997) fitted a model to the data for several metals and showed how the amount of metal deposited in the anomaly could be compared to the historical emission data in a mass balance.

Subsequently, it was decided that the main focus of the GSC MITE Point Sources project should be the Horne smelter at Rouyn-Noranda. The Horne smelter, like the Flin-Flon smelter, is in the Boreal Shield ecozone and is underlain by a mineral-rich greenstone belt covered by podzols and brunisols that support a mixed deciduous and coniferous vegetation, with numerous lakes and swamps that are typical of the Canadian Shield (McMartin et al., 2002). From a logistical point of view, the Horne smelter was better suited for detailed study, as the region has an extensive road network to facilitate field work and is closer than Flin Flon to the majority of the project participants who were based at the GSC in Ottawa. During planning for the GSC MITE, the Horne smelter was also under consideration as the site for several MITE-RN studies, thus facilitating collaboration with university and government partners.

Most papers in this bulletin deal with studies undertaken in the area around the Horne smelter. The contribution by Veillette et al. (2005) introduces the geology and topographic setting of Rouyn-Noranda. Some background on the history of smelting and metallurgical processing at the Horne and Belledune smelters is provided in Appendix B kindly supplied by Noranda, Inc. This topic is also discussed in the paper on characterization of particles in snow by Zdanowicz et al. (2005). Appendix B also provides data on the known annual emissions of particulates and metals from the Horne smelter (Table B1) as well as data on monthly emissions from the Horne smelter covering the two winter periods leading up to the snow surveys in 1999 and 2001 (Table B2). The papers dealing with the area around Rouyn-Noranda describe and interpret data collected during surveys of various surficial geological and environmental media, such as soil, peat, lake sediment and water, trees and snow. The integration of these data provides a comprehensive spatial and temporal description of metal distribution in these sample media within about 100 km (depending on the survey) of the Horne smelter, from which several important inferences can be drawn concerning the extent of smelter influence.

Table 1. List of metal smelters and metal refineries in Canada (*modified from Environment Canada, 1998, Fig. 4.1; McMartin et al., 2002; see Fig. 1*).

# (See Fig. 1)	Site	Company	Smelter	Refinery	Province
1 ¹	Trail	Teck Cominco Limited	Pb, Zn	Pb, Zn	B.C.
2	Fort Saskatchewan	Sherritt International Corporation		Ni, Co	Alberta
3 ¹	Flin Flon	Hudson Bay Mining & Smelting Co.	Cu	Zn	Manitoba
4	Thompson	Inco Limited	Ni	Ni	
5	Kidd, Timmins	Falconbridge Limited	Cu	Cu, Zn	Ontario
6	Sudbury		Ni, Cu		
7	Copper Cliff, Sudbury	Inco Limited	Ni, Cu	Cu, Ni	
8	Port Colborne			Co	
9	Mississauga	Tonolli Canada Limited	Pb ²		Quebec
10 ¹	Horne, Rouyn-Noranda	Noranda, Inc.	Cu		
11	CEZ, Valleyfield			Zn	
12	CCR, Montréal			Cu	
13	Sainte-Catherine	Nova Pb, Inc.	Pb ²		
14 ³	Gaspé, Murdochville	Noranda, Inc.	Cu		New Brunswick
15 ¹	Brunswick Smelting, Belledune		Pb		

¹ see Table 2
² secondary lead smelter
³ closed 2002

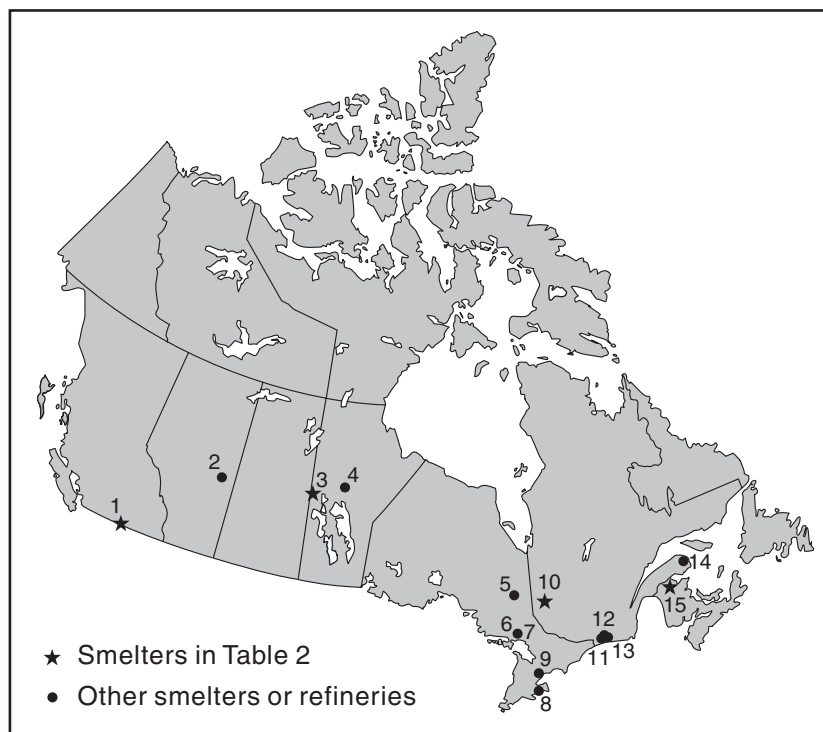


Figure 1. Base-metal smelters and refineries in Canada (*modified from Environment Canada, 1998, Fig. 4.1*)

Table 2. Four smelters considered for study in the GSC MITE Point Sources project (*modified from* McMartin et al., 2002).

	Rouyn-Noranda, Quebec	Flin Flon, Manitoba	Trail, British Columbia	Belledune, New Brunswick
Type of operation	copper smelter (Horne)	copper-Zinc smelter	lead-zinc smelter	lead smelter
Commenced	1927	1930	1916	1967
Company	Noranda, Inc.	Hudson Bay Mining & Smelting Co.	Teck Cominco Limited	Noranda, Inc.
Stacks - number	2	1	52 (1 major)	4 (baghouse stacks)
- height	161 m and 130 m	251 m (since 1974 and 30 m prior to that date)	122 m	48 m, 47 m, 43 m and 37 m
Production	Cu, Se, Ag, Au, Te, Pt and Pd concentrate, CuSO ₄ , NiSO ₄	Zn, Cu, Cd, Pb concentrate, Au, Ag, Se, and Te byproducts	Zn, Pb, Ag, Au, Cd, Bi, In, Ge concentrate, GeO ₂ , CuSO ₄ , CuAsO, NaO ₃ Sb	Refined Pb, Pb alloys, Ag doré, Bi, As, Cu, and Sb co-products, H ₂ SO ₄
Major trace-metal emissions	Zn, Pb, As, Cu, Cd	Zn, Pb, Cu, As, Cd, Hg	Pb, Zn, As, Cu, Cd, Hg	Pb, Zn, Cd, As, Sb, Cu, Hg
Controls on distribution pattern	wind, distance from smelter	wind, distance from smelter	wind, topography, distance from smelter	wind, distance from smelter, oceanographic processes
Main downwind directions	north, southeast	southeast, southwest	northwest, southeast	east, southeast
Ecozone¹	Boreal Shield	Boreal Shield and Plains	Montane Cordillera	Atlantic Maritime
Relief	low — shield terrane	low — shield terrane and carbonate platform	high — 600 m	low — coastal setting
Vegetation	mixed deciduous and coniferous	mixed deciduous and coniferous	coniferous montane forest	mixed deciduous and coniferous; farmland
Bedrock geology	Abitibi Greenstone Belt (Archean): sedimentary and volcanic rocks and associated intrusions	north: Flin Flon Greenstone Belt (Proterozoic) / south: carbonate rocks (Paleozoic)	pre-Pennsylvanian to Eocene sedimentary and volcanic rocks with granitoid intrusions	Ordovician, Silurian, and Devonian mixed sedimentary and volcanic rocks with felsic intrusions
Mineralization on site	Cu-Zn	Cu-Zn	none	none
Surficial geology	extensive glaciolacustrine clay plain developed below ~300 m elevation; large areas of glaciofluvial sand and gravel deposits	shield: thin and discontinuous glacial and glacial-lake deposits, Paleozoic platform: thick, continuous, glacial and glacial-lake deposits	thick deposits of sand, silt, and gravel in terraces within major river valleys (i.e. Columbia River); till and colluvium mantling bedrock at higher elevations	terrestrial: discontinuous loamy lodgement till; marine: beach sediments, varied sediment textures offshore
Predominant glacial transport direction	west-southwesterly	south-southwesterly	southerly	easterly
Other anthropogenic influences	extensive urban development; industries; farming; mining; logging; forest fires	mining and mineral exploration, logging, forest fires; minor urban development	extensive urban development in valleys; fertilizer plant; logging; pulp mills; forest fires; quarrying	extensive urban development; power plants; mining; mercury-cell chlor-alkali plant; pulp mills; ocean dumping
Soil development	good podzols; brunisols	brunisols; poorly developed podzols	podzols and brunisols	podzols

¹ from Wicken et al. (1996)

Parsons and Cranston (2005) describe work undertaken by GSC Atlantic staff near the Brunswick lead smelter in Belledune, New Brunswick. A summary of the historical metal emissions to air and water from this facility is presented in Tables B3 and B4, respectively. The smelter at Belledune differs from the others in listed Table 1 in that it is situated on the coast. Furthermore, because the predominant wind directions are offshore, most stack emissions are carried by the atmosphere away from land and are deposited in Chaleur Bay, a marine environment. The focus of the Belledune study is therefore on the distribution of metals in coastal marine sediments, not on their terrestrial distribution. The coastal sediments are affected by both liquid and airborne emissions.

The Trail smelter is situated in the valley of the Columbia River, close to the Canada–United States border, in the Montane Cordillera ecozone. This smelter was the focus of Point Sources work undertaken by GSC Calgary staff and funded by GSC MITE and Teck-Cominco Metals Ltd. The Trail study was based principally on the use of moss bags as a sampling medium to monitor atmospheric deposition and evaluate the patterns of metal dispersal from the smelter. This work is described in Goodarzi et al. (2003; *see also* Goodarzi et al. 2001, 2002a, b). Originally, the moss-bag methodology was to be used to monitor atmospheric deposition around the Horne smelter and possibly the terrestrial environment at Belledune. This would have complemented the snow and peat surveys carried out at Rouyn-Noranda and strengthened the estimates of present-day atmospheric loading of smelter metals, particularly during summer months. However, this work could not be undertaken due to limited resources. Some preliminary soil studies at Trail have been carried out (Henderson et al., 1999; *see also* McMartin et al., 2002).

During the course of work on the Point Sources project, large amounts of data were collected during sampling surveys of various environmental media. These data have been published and described in various reports, which are listed in the [List of publications](#). In addition, summary data sets have been put together in ArcView® format (*see* /Data directory on this CD). By using no-cost GIS data viewers (supplied on the CD-ROM or downloaded free from the Web) or full GIS systems, interested readers may make their own customized maps, focusing on selected metals, sampling media, locations, or other criteria, and superimpose at will the geology, mineral deposits, roads, topography, and other features supplied on the CD-ROM. This is a useful resource for future research in the area, for teachers and students, and for members of the public who wish to understand more about metals in the environment around smelters.

DISCUSSION

One of the important early outcomes of the Point Sources project was a contribution made to a risk assessment report prepared under the *Canadian Environmental Protection Act* (1988) and published jointly by Environment Canada and Health Canada (2001) on releases from primary and secondary copper and zinc smelters and refineries. It involved a study of emissions from Canada's metal smelters (and metal

refineries) that summarized a variety of data and evaluated the potential for toxicity to the environment. The principle on which the study was based was the establishment of 'critical loads' (deposition rates) of metals, which, if exceeded, would define areas where levels of metal deposition might be harmful to the environment or its biological diversity. The data-gathering phase of the study came at an early stage of the Point Sources project. Nevertheless, the GSC was able to supply data from the 1998 snow survey that provided critical information on metal loading as a function of distance from the Horne smelter.

Because the emphasis of Environment Canada's study was on the levels of bioavailable metal, the data on dissolved metal concentrations in melted snow were particularly valuable as estimates of free ion concentrations. For example, the Environment Canada and Health Canada (2001, Table 18) report shows loading (deposition) rates of soluble metals at various distances from the Horne smelter, using the modelled values based on data from Kliza and Telmer (2001). For other smelters, metal-loading data were obtained from in situ wet and dry deposition samplers. Numerical-dispersion modelling was also applied in order to derive a contoured map of soluble-metal deposition rates for a typical smelter on the Boreal Shield. The snow data and the associated model for rates of metal loading as a function of distance from the smelter (Bonham-Carter et al., 2005; Kliza et al., 2005) provided key information for the risk-assessment study.

Many other results described in this bulletin can be used to support risk-assessment studies and risk-management decisions at smelters across Canada and elsewhere. Although a number of isolated studies have been carried out on metal distributions in environmental media around smelters, the integrated approach taken around Rouyn-Noranda is unique in Canada, and few such studies have been undertaken elsewhere in the world.

The methodologies applied here can serve as a model for studies to be executed around other point sources of metals. The GSC MITE Point Sources project illustrates the important role to be played by geoscience in providing the necessary scientific knowledge required by policy makers for regulating the metals industry.

CONCLUSIONS

The footprint around the Horne smelter, defined as the zone within which total copper concentration or loading exceeds background levels (allowing for variability), is approximately circular with a radius of 65 km, with about 5 km more downwind and 5 km less upwind. Metal-loading values, along with a model of how these values change as a function of distance and direction from the smelter, are invaluable for risk-assessment studies. The general size and shape of the footprint differs depending on sampling media, metals, and wind direction. However, in every case, metal levels decrease exponentially with distance from the smelter (Bonham-Carter et al., 2005; Henderson and Knight, 2005; Kettles, 2005).

The spatial extent of the main smelter footprint alone is not a guide to the distance of transport of emissions by the atmosphere. The metal contained within the anomaly centred on the smelter does not account for all the reported emissions for the periods studied. The proportions of the emissions accounted for are approximately 25 to 50% for Cu, 10 to 20% for Pb, 25% for Zn, 5% for As, and 20 to 25% for Cd, from a comparison of two snow surveys and a peat-hummock survey carried out in the Point Sources project. Metal emissions not accounted for by deposition within the anomaly must be transported at least 150 km from the smelter. Thus, if the reported emissions have not been overestimated, at least 50% of the Cu, at least 80% of the Pb, 75% of the Zn, 95% of the As, and 75% of the Cd (Bonham-Carter et al., 2005) are subject to long-range transport. Dendrochemical (tree-ring) archives from spruce trees reveal that the effects of smelter emissions can be detected in stable isotope (C, H) values from soon after the Horne smelter began operation in 1927, due to increased levels of SO₂ that were absorbed by spruce needles. Levels of Pb and Cd in tree rings increased about 15 years later, as uptake of these metals occurs primarily through plant roots (Savard et al., 2005). These changes in concentrations coincide with the detection of a new Pb type that is of smelter affinity. This indicates that heavy metal isotopes in natural archives can be useful to decipher the sequence of incoming atmospheric metals.

Metal emissions that are deposited on soil are predominantly held in the organic humus layer. There is evidence that within a few kilometres of the smelter, metal of smelter origin is leached downwards into the B and C soil horizons (Henderson and Knight, 2005).

A model of metal loading rates as a function of distance from the smelter, defined mathematically by fitting a three-parameter model to survey data (particularly snow and peat), is valuable for studies on the biological effects of smelter emissions, and for risk-assessment studies (Bonham-Carter et al., 2005).

The interpretation of maps showing metal levels in the coastal marine environment near the Belledune smelter is complex because of the presence of other nearby anthropogenic metal sources (Parsons and Cranston, 2005) and the dispersion of smelter emissions by tides and currents. Nevertheless, the effects of the smelter are evident to a distance of at least 20 km from the smelter.

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has been very helpful to those working on the Brunswick smelter study. He provided the process description for Belledune and discharge data for atmospheric emissions and waste water (see Appendix B). The manuscript was improved by constructive reviews from Bob Garrett (GSC Ottawa), Mike Parsons (GSC Calgary), and Robert Prairie.

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Appendix A

Responses to key questions

Question 1

What are the shape and size of smelter ‘footprints’, as seen in regional geochemical surveys of soil, snow, water, sediment, and vegetation?

Answer

The size and shape of the smelter footprint depend on the type of metal and on the sampling media. A typical element such as Cu has a footprint that is approximately circular with a radius of between 60 and 70 km from the smelter. Beyond the footprint, metal from the smelter cannot be reliably distinguished from metal from other sources. Varied proportions of the reported metal emissions are transported beyond the footprint, but once these metals have been deposited on the ground and mixed with metals from other sources, they become too dilute to be reliably distinguished according to origin, unless isotopic methods are used.

Question 2

Can the metals present in samples collected at various distances from a smelter be apportioned into ‘anthropogenic’ (i.e. emitted from a smelter or other human sources) and ‘natural’ sources?

Answer

Source apportionment can be determined indirectly by use of a model fitted to data on metal concentration as a function of distance from the smelter. Metal concentration approaches an asymptotic value at a large distance from the smelter, and this asymptote can be treated as a background value. By assuming that background deposition occurs everywhere, the ratio (observed concentration minus background concentration) to background concentration can be used as a proxy for the ratio of smelter to non-smelter sources of the metal. This is not necessarily the same as the ratio of anthropogenic to natural sources, because metals from other anthropogenic sources (e.g. from other industrial and metropolitan sources) may be present in the atmospheric background. Evidence exists to show that the proportions of some metals in the loosely bound phase in soil and peat samples (as determined by selective leach analysis) are more abundant closer to the smelter than farther away. However, this does not provide conclusive evidence of source apportionment. No systematic use of stable isotopes for fingerprinting smelter emissions in various sampling media was attempted, mainly because the smelter feed is complex, with multiple sources, making isotopic characterization difficult. However, stable isotopes of C and H provide indirect evidence of smelter influence, as seen in dendrochemical time series (see Question 5).

Question 3

What does the study of the geological environment reveal about the chemical and mineralogical forms of metals in surficial media around smelters, and can the availability of smelter-emitted metals to biota be determined?

Answer

Particles of smelter origin in snow and humus have shapes and textures that reflect a variety of smelter processes. Particles in snow differ from particles in humus in having a greater proportion of soluble forms. The geochemical data from snow provide information about the relative solubility of smelter metals and in some cases how this changes with distance from the smelter. Bioavailability cannot be determined, but free-ion activity, sometimes used as a proxy for bioavailability, is indicated by the concentration of soluble metal in the snow samples. The ratio of labile to total metal in soil and in peat increases in some soil horizons and for some elements with decreasing distance from the smelter. This may provide indirect evidence of a higher proportion of easily dissolved metal in environmental media close to the smelter, although it is not hard evidence of bioavailability.

Question 4

What can we learn about the history of metal deposition from the atmosphere from natural archives such as lake sediments, tree rings, and peat deposits in the vicinity of smelters?

Answer

The dendrochemical (tree ring) results from this study provide archival information about the date of smelter start up, because stable isotopes of C and H change markedly in rings that are dated to the late 1920s. This effect was produced by increased atmospheric SO₂ levels and foliar intake. Levels of Cd and Pb increased in rings about 15 years after smelter start up; this delayed effect is due to the fact that these metals are taken up by tree roots. Vertical profiles through peat hummocks show a shape for Cu, Pb, and Zn that shows a peak at depth indicating that metal deposition increased from a natural background level as a result of smelter emissions, then decreased again in response to reduced emissions in more recent years. The effect of diagenesis on metal profiles in lake-sediment cores is still under active study and no conclusions about this aspect of the work are included here. However, a regional picture of pre- and post-smelter metal levels in nearly 100 lake-sediment cores indicates that post-smelter metal levels are much greater than pre-smelter levels, and this effect decreases with distance from the smelter, providing an independent estimate of the smelter footprint.

Question 5

Can we determine how far smelter emissions travel in the atmosphere from the study of surficial materials?

Answer

The sampling media used in GSC MITE studies provide evidence for metal loading from the atmosphere as a function of distance from the smelter. The smelter footprint is defined as the area within which metal levels are definitely distinguishable from background levels. The calculation of the amount of metal contained in the 'above background' zone around the smelter is significantly less than the total metal emitted from the smelter in recent years (as seen in both snow and peat-hummock data). Therefore, at least some proportion of the metals emitted from the smelter is being transported by the atmosphere beyond the smelter footprint. Smelter-emitted metals deposited outside the footprint are too dilute to be distinguished reliably from metal from other sources. In this study, no estimate of a maximum distance of transport was possible.

Question 6

Can a predictive model be constructed that can be used to estimate the rate of deposition of metals from smelters as a function of wind direction and distance from source, on the basis of evidence from surficial environmental media?

Answer

Yes. A mathematical model fitted to observed data can be used to predict the rate of metal deposition from the atmosphere as a function of distance from the smelter. The coefficients of this model can be determined from fitting to metal concentration data (or metal loading data where available). Several examples of these results are shown for metals in snow and other sampling media. Where sufficient samples are available, the effect of wind may be evaluated by modelling with subsets of data points, selected according to wind direction. In general, the effect of wind on deposition patterns is not as strong as might be expected, although this does not necessarily apply to net transport of metal by the atmosphere.

Appendix B

Noranda's Horne smelter: smelter process description

**Stephane Robert, Noranda, Inc.,
Rouyn-Noranda, Quebec**

The Horne smelter started production in 1927 to process copper concentrates produced by an associated mine-mill complex. Prior to the 1970s, the smelter utilized conventional copper-smelting technology including reverberatory furnaces and Peirce-Smith converters. Development and installation of Noranda's patented reactor for the treatment of copper concentrates permitted the gradual elimination of the reverberatory furnaces. The mine closed in 1976 and an H₂SO₄ plant entered service in 1989. The smelter now processes custom and toll copper concentrates and secondary materials from over 200 suppliers. Noranda's business strategy is based on the unique flexibility of its process technology, which allows the smelter to overcome a logistical disadvantage and accept feed materials from five continents. The Horne's niche is in processing complex feed materials with high levels of metals and/or impurities. The smelter is able to maintain efficient operation, achieve a high level of metal recovery, and control impurities and emissions in spite of wide differences in feed quality.

Emission reduction efforts have continued through the 1990s and are ongoing. The efforts undertaken to date have included local and adjacent site cleanup, and numerous improvements to the smelter process, emission controls, and ambient air monitoring and response. In 1994, the emission of fugitive particulates from stockpiled concentrates was reduced by constructing a concentrate storage building. Since that time, some concentrates delivered to the site in railcars have been unloaded within the confines of the concentrate storage building.

In 1995, Noranda completed its design for a new pyrometallurgical vessel now known as the 'Noranda continuous converter', to reduce SO₂ and particulate emissions from the Peirce-Smith converters and direct more off-gases to the sulphuric acid plant. The new Noranda continuous converter was commissioned during 1997–1998. The new converter processed about 70% of the reactor matte — this percentage will approach 100% during the year 2003–2004. The Peirce-Smith converters are now used to process the Noranda converter semi-blister copper. The final product, copper anodes, is shipped to the Noranda, Inc., CCR Division copper refinery in Montréal-Est, Quebec.

Smelter feed includes both contract and toll concentrates and recycled materials containing copper and precious metals. The feed is obtained from over 200 suppliers including mines in the Abitibi region of Quebec and mines located internationally. At present, about 1.1 million tonnes of feed are processed annually including about 150 000 tonnes/a of recycled materials. In 2001, Noranda Horne's copper production was 190 000 tonnes.

Table B1. Annual atmospheric emissions data for the Horne smelter, Rouyn-Noranda, Quebec, also summarizing the amount of concentrate processed by the smelter (feed) from the first year of operation in 1928 until 2001. Data for SO₂, particulates, Pb, Zn, and Cu are available for 1965–2001, for As, from 1969, and for Cd, from 1974. Data kindly supplied by Noranda, Inc.

Year	Feed (tonnes)	SO ₂	Particulates	Pb (tonnes)	Zn	Cd	As	Cu
1928	246 687							
1929	388 475							
1930	665 939							
1931	694 489							
1932	833 310							
1933	916 827							
1934	953 164							
1935	976 341							
1936	1 016 459							
1937	1 048 483							
1938	1 171 803							
1939	1 211 361							
1940	1 236 206							
1941	1 280 414							
1942	1 247 511							
1943	1 252 584							
1944	951 126							
1945	837 414							
1946	681 575							
1947	581 869							
1948	758 814							
1949	958 694							
1950	1 128 265							
1951	1 112 761							
1952	1 133 564							
1953	745 720							
1954	1 031 032							
1955	1 161 195							
1956	1 146 717							
1957	1 182 817							
1958	1 363 477							
1959	1 356 016							
1960	1 397 913							
1961	1 411 588							
1962	1 425 200							
1963	1 446 743							
1964	1 483 673							
1965	1 565 053	710 000	9600	1400	1500			250
1966	1 490 527	660 000	9500	1500	1500			240
1967	1 445 939	640 000	14 000	1800	3000			410
1968	1 464 048	640 000	14 000	2200	2800			380
1969	1 440 278	640 000	12 000	2200	2300		600	220
1970	1 401 684	620 000	10 000	1800	2300		470	200
1971	1 40 5800	600 000	12 000	2100	3100		330	320
1972	1 346 081	580 000	12 000	2400	2700		460	320
1973	1 406 320	600 000	8300	1600	1700		370	230
1974	1 423 669	620 000	10 000	1700	2400	110	280	270
1975	1 209 419	560 000	7400	1200	1600	140	220	210
1976	1 159 333	560 000	8200	1700	1700	150	170	160
1977	1 196 160	540 000	8600	1700	1800	130	170	180
1978	1 058 888	520 000	7300	2000	1300	140	260	120
1979	1 140 981	560 000	7800	2000	1400	150	220	110
1980	1 047 493	560 000	7200	1700	1300	150	220	100
1981	1 002 174	520 000	5900	1300	1000	170	210	90
1982	1 106 507	560 000	6000	1200	1000	160	230	120
1983	910 098	480 000	4400	1100	680	70	150	80
1984	964 976	460 000	3800	1100	500	40	160	70
1985	900 475	440 000	3800	1000	450	40	150	70
1986	708 094	360 000	2900	930	330	30	70	60
1987	805 085	420 000	4100	930	560	20	160	70
1988	873 740	420 000	2900	850	420	39	113	74
1989	633 256	300 000	2300	620	290	10	80	60
1990	746 601	144 000	1000	280	80	5	40	60
1991	778 747	160 000	820	190	60	4	20	90
1992	743 047	166 000	810	160	70	6	24	130
1993	794 254	168 000	720	195	70	4	18	73
1994	853 551	154 000	770	260	62	3	19	70
1995	881 025	172 000	940	340	85	3	29	58
1996	934 187	148 000	1200	300	85	2	63	65
1997	896 863	144 000	870	197	55	1.4	55	50
1998	881 283	112 500	920	150	39	2.4	78	70
1999	829 017	94 000	720	100	23	1.6	64	69
2000	787 696	90 000	620	80	19	2.2	59	59
2001	840 233		595	65	18	2.5	98	42

Table B2. Monthly atmospheric emissions data from the Horne smelter, Rouyn-Noranda, Quebec, for periods covered by two snow-sampling surveys in March 1998 and March 2001. Data supplied by Noranda, Inc.

Month/ year	Particulates	Cu (tonnes)	Pb	As	Cd
11/1997	60.17	4.02	22.00	5.57	0.15
12/1997	51.45	4.57	25.31	7.06	0.07
1/1998	49.56	4.69	15.53	5.80	0.07
2/1998	64.07	5.82	14.94	4.38	0.06
3/1998	78.13	7.16	13.22	7.08	0.06
11/2000	61.57	5.90	8.07	5.95	0.09
12/2000	61.75	8.95	3.23	5.27	0.03
1/2001	59.77	7.45	5.03	5.01	0.03
2/2001	52.42	5.33	4.47	7.63	0.10

Process description

The concentrate feed is combined with recycled feed materials (e.g. selected electronic scrap materials) and other concentrates produced at the smelter through the reprocessing of slag and collected dusts (*see* Fig. B1). The material is control fed to the Noranda reactor, which operates at a temperature of approximately 1230°C. The reactor process is monitored continuously. Matte and slag are removed, as required, from the reactor through tap holes.

The Noranda reactor matte is processed in the Noranda continuous converter to produce semi-blister copper, or on a batch basis in the Peirce-Smith converter to produce blister copper. The semi-blister copper from the Noranda continuous converter is treated in a desulphuration vessel to complete the sulphur oxidation prior to the anode furnace. The blister copper is then processed in an anode-refining furnace

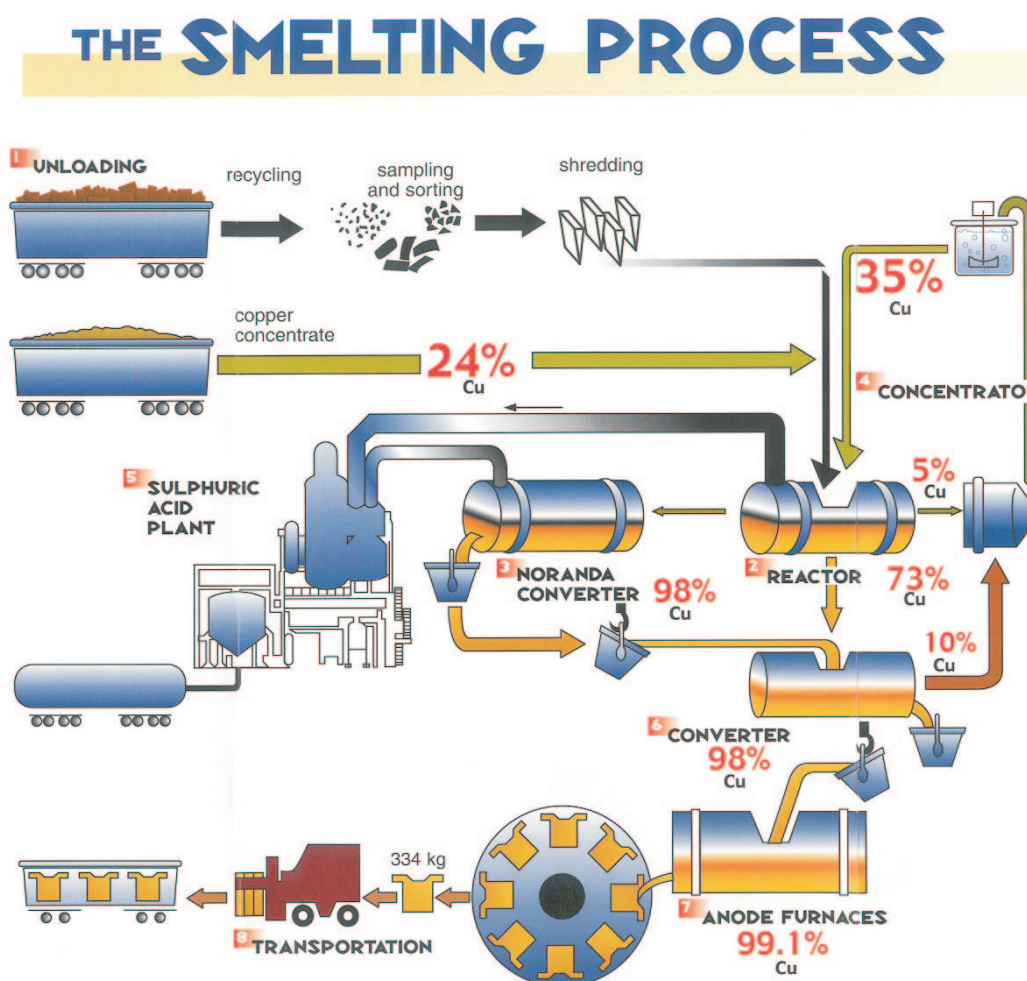


Figure B1. Process diagram for the Horne smelter, Rouyn-Noranda, Quebec (courtesy of Noranda, Inc.)

to remove most of the dissolved oxygen and sulphur. The product is then cast into copper anodes that are shipped to Noranda's CCR refinery for electrolytic refining of copper and precious metals.

The various slags are collected in ladles and transported to a slag-ladle cooling yard where the ladle contents are slowly cooled using water or air. The cooled slag is broken using a boom-mounted hammer and transported to an enclosed crusher. The crushed slag is processed in the slag concentrator to produce a concentrate for recycling to the Noranda reactor. The rejected slag materials are slurried and disposed of in a tailings impoundment area.

Noranda reactor — Noranda converter aisle

The Noranda reactor and the Noranda continuous converter are located in the same building. The main process gases and particulate streams from these vessels are collected, passed through a dry electrostatic precipitator, and then treated in the acid plant. The cleaned gases are released to the atmosphere using the acid-plant stack. The collected dusts are regularly bled from the system and a portion is returned to the Noranda reactor for copper recovery. A portion of the dust, which contains a high level of lead, is segregated, and then lime treated and disposed of with the concentrator tailing slurry.

Peirce-Smith converter — anode furnace aisle

The principal function of the Peirce-Smith converters is to oxidize sulphur to SO_2 and reduce the copper to its metallic state. Oxygen-enriched air is injected into converters to convert iron sulphide to iron oxide, which in turn combines with flux to form an oxide slag separate from the copper sulphide matte. This slag has a high copper content and as such is collected and reprocessed with the reactor slag to produce the slag concentrate.

The primary process gases from the operations along the Peirce Smith converter–anode furnace aisle are collected and treated using dry electrostatic precipitators. The cleaned gases are directed to Stack 2 as the SO_2 concentrations are both intermittent and low compared to those upstream at the Noranda reactor and continuous converter.

Noranda changed the process at the Horne smelter gradually since 1997 to achieve 90% sulphur fixation by the end of the year 2003–2004. Since the beginning of the GSC MITE (1997) and MITE-RN (1999) programs, SO_2 emissions and particulates at No. 2 stack have decreased by more than 30%.

Noranda's Brunswick smelter: smelter process description

**Paul J. Deveau, Environmental Superintendent,
Brunswick smelter, Noranda, Inc.,
Belledune, New Brunswick**

Figure B2 is a flow diagram for the Brunswick lead smelter showing the general sequence of the major unit operations, from the receipt of raw materials to the production of metals.

Lead-bearing materials are received by road, rail, or sea, both in bulk and in drums or other packages. Lead-bearing materials are unloaded and stored in buildings. A battery breaker and a new facility for concentrate handling and storage were commissioned in 1996. Battery plates and pastes

Table B3. Annual atmospheric emissions from the Brunswick lead smelter, Belledune, New Brunswick. Data supplied by Noranda, Inc.

Year	SO_2	Particulates	Pb (tonnes)	Zn	Cd	As
1975		362	176	41	6	23
1976		155	66	16	6	7
1977		182	89	16	6	7
1978	25 096	114	53	10	4	2
1979	19 466	123	54	10	6	4
1980	12 830	127	60	6	3	2
1981	22 144	148	62	9	5	4
1982	23 144	109	52	6	4	5
1983	18 406	107	46	7	4	5
1984	10 558	135	59	4	3	6
1985	17 326	205	90	6	9	7
1986	20 284	258	95	9	6	26
1987	16 450	109	39	11	10	3
1988	21 104	147	56	2	3	5
1989	21 618	162	49	13	3	6
1990	5 459	67	29	3	2	2
1991	5 165	35	12.8	2.0	3.2	0.9
1992	10 661	101	19.4	3.2	3.2	2.1
1993	5 694	80	21.7		3.6	5.5
1994	11 840	33	8.8		1.9	1.3
1995	12 056	32	12.2		1.7	2.0
1996	11 467	68	17.0		1.7	1.7
1997	12 001	30	14.6	1.0	0.7	1.9
1998	12 770	116	11.8	4.3	2.9	3.2
1999	12 219	67.07	8.94	1.78	0.85	3.78
2000	11 938	86.01	13.89	2.43	1.36	1.49

Table B4. Trace-metal content of waste-water treatment plant effluent at the Brunswick lead smelter, Belledune, New Brunswick. Annual average values. Data supplied by Noranda, Inc.

Year	Discharged volume m^3	Pb mg/L	Zn mg/L	Cd mg/L	As mg/L	Cu mg/L	Fe mg/L
1981	926 290	0.19	2.03	0.39	3.16	0.010	0.33
1982	926 290	0.14	1.36	0.67	5.32	0.017	0.38
1983	954 092	0.13	1.48	0.90	11.49	0.036	0.36
1984	898 488	0.13	0.68	0.23	8.44	0.041	0.26
1985	694 964	0.43	0.49	0.20	3.46	0.042	0.24
1986	716 412	0.92	0.92	1.22	3.38	0.053	0.53
1987	716 323	0.21	0.75	0.59	0.68	0.038	0.56
1988	846 691	0.11	0.16	0.16	0.28	0.033	0.13
1989	657 914	0.17	0.11	0.05	0.58	0.059	0.19
1990	671 593	0.12	0.14	0.07	1.20	0.043	0.76
1991	740 452	0.07	0.14	0.14	0.30	0.037	0.26
1992	738 383	0.09	0.24	0.42	0.14	0.026	0.26
1993	786 514	0.06	0.28	0.11	0.09	0.042	0.17
1994	723 387	0.13	0.32	0.05	0.07	0.08	0.18
1995	698 068	0.06	0.24	0.03	0.08	0.04	0.19
1996	818 200	0.04	0.17	0.02	0.05	0.023	0.14
1997	818 545	0.04	0.194	0.027	0.072	0.023	0.11
1998	1 036 280	0.06	0.35	0.025	<0.05	0.025	0.33
1999	1 092 417	0.04	0.242	0.018	0.05	0.021	0.15
2000	1 056 052	0.036	0.27	0.017	0.022	0.02	0.205

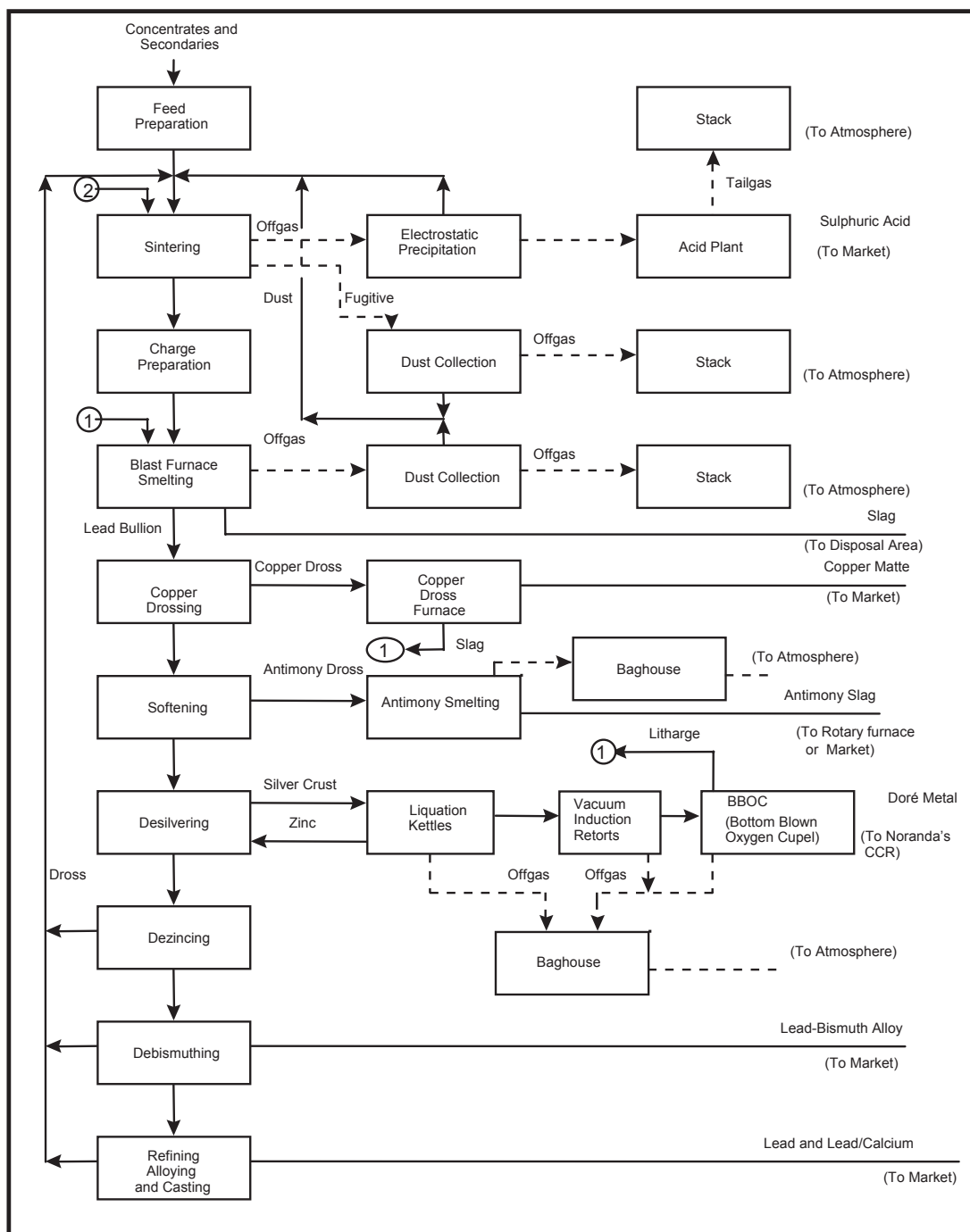


Figure B2. Process diagram for the Brunswick smelter, Belledune, New Brunswick (courtesy of Noranda, Inc.)

are processed, plastics are sold for recycling, and acidic wash water is collected and used for pH control at the waste-water treatment plant.

In the proportioning plant, the lead concentrate, limestone and silica are proportioned to form a low-viscosity, low melting point FeO-CaO-SiO_2 slag with low lead content and suitable refining properties. New feed is mixed with recycled materials from the smelter and processed in a sinter machine

to oxidize sulphide sulphur to SO_2 . Moisture is added to sinter-plant return fines and fresh feed to produce a porous and reactive basic lead-iron silicate sinter with suitable mechanical properties.

The sinter plant off-gas is processed through an electrostatic precipitator that removes the bulk of the dust for recycle to the sinter plant. Strong off-gases are treated by a Venturi scrubber and wet electrostatic precipitator, cooled, and directed

to a single-absorption H_2SO_4 plant for conversion to H_2SO_4 . Weak gases are treated by the sinter baghouse prior to discharge. Moist gases from the sinter machine and sinter recycle cooling containing submicron fines are treated by wet scrubbers. All emission-control dusts from the sinter plant and gas cleaning are returned to the sinter machine as a dust or slurry, except if electrostatic precipitator dust is required to be bled from the circuit to control impurity levels.

Sinter at <2% sulphur is processed in a blast furnace using metallurgical coke as both a fuel and a reductant to reduce lead oxide to lead metal. Blast air is enriched with oxygen in order to reduce energy consumption. All off-gases from the blast furnace are cleaned by a baghouse so as to remove total particulate matter prior to release. Furnace baghouse dust is returned to the sinter machine as a slurry, except as required to be bled from the circuit to control impurity levels. The lead bullion and the slag are continuously tapped from the furnace and separated. Slag is granulated by quenching with water to preserve the environmentally stable, high-temperature, vitreous structure and is dewatered and trucked to an engineered impoundment area.

Two short rotary furnaces are used primarily for the melting of scrap battery plates but may also be used to further process a wide variety of smelter or refinery byproducts. Off-gases from the short rotary furnaces are treated by a baghouse prior to release.

Lead bullion is processed in batches by a thermal refinery using the conventional kettle method to produce refined lead at >99.9% Pb and specialty lead-cadmium alloy. Pumps in some sections have replaced bailing or pouring of lead bullion in order to minimize safety risks and lead re-oxidation. The lead refinery is ventilated to minimize worker exposure and all off-gases are treated by a baghouse prior to release.

Copper dross is first removed and processed in a reverberatory furnace in order to recover entrained lead and other values by separating the following four distinct phases:

- an oxide slag containing iron and zinc,
- intermetallic speiss containing copper arsenide, copper antimonide, and copper stannide and enriched in silver and gold,
- copper-lead sulphide matte enriched in silver,
- metallic lead bullion enriched in silver and gold.

Matte and speiss are sold for processing by a copper smelter. Bullion is further refined by removing residual copper with sulphur, softening the lead by oxidizing residual antimony, tin, and arsenic with caustic soda, removing silver by precipitation with zinc, removing zinc with caustic soda, removing bismuth with magnesium and calcium, and finally removing any residual impurities with caustic soda.

Zinc-silver crust is oxidized to produce Doré metal, an impure silver bullion containing more than 96% silver that is shipped for further refining.

Other refinery byproducts may be further processed or sold.

Refined lead may be alloyed with calcium, tin, or antimony prior to casting into a variety of shapes for shipment to customers.

A recycled process-water system collects process water from the sinter and acid plants for reuse in order to minimize raw water use and metal discharges to the environment. Under normal operating conditions, there is no discharge. Any surplus process water is directed to the cooling recycle pond, which receives slag granulation water as well as surface water. Water from the cooling recycle pond is used for slag granulation and cooling of the furnace top.

A waste-water treatment plant treats all excess water prior to discharge for removal of arsenic, cadmium, lead, copper, zinc, and other metals by lime neutralization and air oxidation of iron and arsenic to precipitate metal hydroxides and gypsum. Water-treatment sludge is reprocessed by the smelter.