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Report on study period at the Geological Survey of Finland, April 2008

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Norges geologiske undersøkelse
Geological Survey of Norway

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REPORT

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Summary: The report compares some aspects of the activities of the Geological Surveys of Finland and Norway and suggests a number of means by which cooperation between the two organisations can be developed. The appendices are two papers on which the writer worked during a period of study leave in at the Geological Survey of Finland office in Espoo.

Keywords:	Geological survey	Finland
Russia	Emissions	Nickel
Copper		

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Introduction

The purpose of the application for a Nordic Exchange Scholarship was stated as follows: *Ore geology and regional geochemistry, two fields in which I am currently involved, have had a very high priority in GSF for many years, including not only work within Finland but also large-scale international compilations with partners in neighbouring countries and the rest of Europe. Almost inevitably this work has led to GSF developing sophisticated solutions for processing and presentation of the data in these (and other) fields. I hope to use the planned stay in Finland: 1) To learn more about the GSF solutions for presentation of data on ore deposits: Finnish experience can have great value for NGU in a period where we, at NGU, aim to improve our performance in this respect, 2) Along with Finnish colleagues to work towards an improved understanding of how knowledge about ore deposits can be used to better interpret data relating to pollution, represented by, e.g. regional geochemical data and estimates of emissions from industry.*

This report gives a summary of what was learned and achieved during a stay at the Head Office of the Geological Survey in Finland (GTK) at Espoo during the month of April, 2008. The writer was given optimal working conditions by GTK and is very grateful to the organisation for its generosity and to many colleagues there for their friendly assistance and dialogue.

Comparison between the Geological Surveys of Finland and Norway

<u>GTK</u>

Several of the most positive projects in the writer's career have involved cooperation with Finnish geoscientists, mainly from GTK but also from the University of Turku. The period of study at GTK offered a different type of experience of the organization, leading to the conclusion that a comparison of some of the characteristics of GTK and NGU in their respective national contexts was a useful background for consideration of ways in which NGU can learn from, and cooperate with GTK in the field of ore geology (and in other areas).

GTK is one of the larger geological surveys in Western Europe, despite the privatisation of its drilling activities some years ago, and of most of its chemical laboratory functions in 2007. The latter, with a staff of c. 100, now form the company Labtium, with major facilities in Rovaniemi, Kuopio and Espoo. One of the reasons for the size of GTK is the priority given to development of mineral resources in Finland after WW II, as an end in itself, but also as a means of payment of reparations to the Soviet Union (following on the Winter War of 1939-40 and the Continuation War of 1941-44). These goals were achieved through a strong symbiosis between GTK, which provided comprehensive basic data and, in many cases detailed assessment of individual ore and mineral deposits, and Outokumpu, the major national mining company up to the early part of this decade. GTKs importance can be judged by the fact that its Board of Directors currently includes senior representatives of the Ministry of Trade and Industry, the Ministry of the Environment and the Finnish National Fund for Research and Development: its chairman comes from the management of Boliden AB, the largest mining house in the Nordic region.

GTK is *"tasked with ensuring companies and decision-makers have complete information on the location, accessibility, size and quality of mineral deposits."* (Director General E. Ekdahl, GTK Annual Report for 2005). The political priority given to GTK, and, within its mandate, to the mineral sector is reflected in its level of support from the Finnish government. There is, within its activities in the mineral sector, a clear focus on exploration for, and assessment of metal deposits. The organisation, and its staff have been able to take a long-term, strategic view, encompassing development of expertise relevant to most if not all of the types of resources for which Finland has a potential. Their activities have been supported by cooperation with university institutes in Finland, at least three of which maintain strong involvement on ore-geological research. The priority given to exploration for metal deposits in Finland has enabled GTK to provide industry and decision makers with information on mineral potential and specific deposits of a quality which is probably unrivalled in Europe. This has given Finland a strong position in the period of increasing prices and demand for metals since 2003, as is clearly indicated by the number of international prospecting companies which have established projects in Finland, and the number of new mines which have been opened or are being planned.

	Finland/GTK	Norway/NGU
Land area of country (km2)	338 144	323 802
Land use	10% water, 69% forest, 8% farmed	5% water, 37% forest, 3% farmed
Population	5 300 000	4 600 000
Survey staff (end 2007)	773	225
Survey budget, mill. NOK (2007)	474.4	195.9
% external funding	23.6	31.8
Major offices	4	1
% mineral related	40.7	26.2
Active metal mines (2007)	7	2
Active industrial mineral mines/quarries (2007)	28	37
Value of metal/mineral production, mill. € (2004)	533	820

Table 1: Comparison of various features of Finland, GTK and the Finnish mineral industry and of Norway, NGU and the Norwegian mineral industry.

GTK has a strong regional focus: the Espoo facility houses a staff of c. 420 but there are major offices in Rovaniemi and Kuopio (c. 100 each) and a recently established smaller office at Kokkola.

GTK's web site clearly reflects the institution's strategic priorities and the level of resources available both for its technological framework and its content in prioritised sectors. GTK's site reflects its responsibility for certain activities which are not currently part of NGU's mandate (and which are handled by the Mines Inspectorate in Norway – though see below). The web site reflects the capacity which GTK has been able to devote to prioritised topics, e.g. gold mineralisations in

Lapland, which has also allowed the organisation to publish a major collection of papers on this topic (Ojala (ed.), 2007).

NGU

The number of employees at NGU is approximately average in relation to the size of the country, when compared with other geological surveys in Western Europe. The organisation covers approximately the same spectrum of disciplines as did GTK prior to the creation of Labtium, but with much smaller numbers. Each organisation has some activities not found in the other, e.g. major groups working on documentation of peat resources and on long-term, contract mapping projects outside Europe at GTK and smaller groups working on landslide research and mantle dynamics at NGU. NGU has a small office in Tromsø, linked to activities in the Polar Environmental Centre but does not have the form of decentralisation found in GTK. A further contrast between the organisations is that GTK clearly has a much greater level of technical support staff in its organisation (10% with Ph.D., 32% with other university degrees, 58% without university degree (GTK Annual Report, 2006)) than NGU (31% with Ph.D., 31% with other university degrees, 38% without university degree).

The mining industry in Norway has a long history, extending back to the early 1600s in several parts of the country and playing a major role in the national economy in various periods. No dominant mining house of the type of Boliden or Outokumpu developed in Norway. The period since the 1960s has seen a decline in metal mining and a marked increase in the production of industrial minerals in Norway. 37% of the value of non-fuel mineral production in Norway in 2005 was industrial minerals, while just over 9% consisted of metals (40% was construction materials and 14% natural stone). Just below 6% of the production of construction materials was for export: the remainder reflects the level of investment in major domestic construction projects, including those for the oil industry, the rise of which has coincided with the decline of the metal-mining industry in Norway.

NGU had a stronger focus on mineral resources, especially metal deposits, up to the 1980s, including individual projects involving detailed exploration of specific metallogenic provinces (e.g. Grong and inner Finnmark) and deposits (e.g. Bidjovagge and Bruvann). The period up to 2006 saw a progressive decline in the level of NGUs activities within ore geology (and regional bedrock geology), in parallel with diversification to other aspects of applied geology, international activities and a more general emphasis on research. One consequence of these changes is that the organization no longer has "blanket coverage" of regional expertise in mineral resource or bedrock geology for the whole country. A further development is that the organisation's expansion and increasingly decentralised form of organisation have "driven" it in certain directions in which external funding has been readily available in the medium- and long term (many of them related to the oil industry or climate change), whereas disciplines in which external funding is more limited and usually short-term have had more limited possibilities for development, even though they are important components in NGUs core functions and may be fundamental to many of the other, better-funded activities. Among the challenges presented by this situation are.

1. Access, within Norway, to the skills necessary for implementation of projects in new fields is limited, especially when NGU is competing with the oil industry.
2. The educational system is also being "driven" by the availability of external funding, to some extent at the expense of the development of basic skills, many of which involve fieldwork on land.
3. Retraining/refocus within an organisation is a long-term process and should only be implemented after serious strategic consideration: it is a process which is not easily reversed as a result of changed priorities (e.g. due to the dramatic increase in interest in ore deposits within recent years).

NGU's team for industrial mineral and metal deposits currently has 15 members, several of whom have skills at very high levels within their fields of specialisation and all of whom have strong expertise within parts of the field. 6 of the team have Ph. Ds. and only one does not have a university degree (i.e. there is almost no possibility for allocation of tasks not requiring academic qualifications according to the level of professional skills actually needed for them). The team numbered only 9 for much of the period 2001-2006.Their collective record, in terms of reporting, publication and other outreach activities is strong. This level of manpower has, inevitably, not allowed the team to match the performance of an organisation such as GTK: this applies not only to the capacity allocated for mineral resource activities as such, but also to the capacity available for IT support. The capacity available does not allow NGU to match the performance of GTK in relation to:

1. Digitalisation and user-friendly presentation of the enormous volume of data on ore and mineral deposits in Norway (2,350 industrial mineral deposits and 4,513 ore deposits).
2. Focus on detailed studies of ore deposits and provinces such as that published by GTK in 2007: "Gold in the Central Lapland Greenstone Belt (Ojala, 2007).

Some conclusions

Several strategies can be employed to enable NGU to benefit from GTK's expertise and scale, and to enable GTK to benefit from areas in which NGU has particular skills:

1. <u>Scientific cooperation:</u> There are several examples of successful cooperation at the regional scale, especially involving map compilation and geochemical mapping N of the Arctic Circle, most of them also involving Swedish and/or Russian partners as well. Within the last month a concept for Norwegian-Finnish-Russian cooperation on gold mineralizations in northern areas has been developed. Participation in this project will necessitate allocation of appropriate resources in NGU, but will lead to a significant development of expertise in a prioritised field. It should be possible to have similar cooperative projects on a more local scale: Such projects have been carried out with Russian partners across the border in the Sør-Varanger area, but no bilateral Norwegian-Finnish projects have been implemented on, e.g. ore deposits of similar types in adjacent parts of the two countries.

2. Database cooperation: The project Fennoscandian Ore Deposit Database (FODD) is a good example of the benefits which can be achieved collectively and for the individual participants (GTK. NGU, SGU, VSEGEI (St. Petersburg) and SC Mineral (St. Petersburg) when the parties agree on a common structure for compilation of databases. The products (the database itself and, so far, one derived overview map and another planned) are important for scientifically for the participants and their users. They are also important as a means to illustrate the ore potential of the Nordic countries and NW Russia in a time when European authorities are becoming increasingly concerned about access to supplies of strategic minerals.
3. Participation in each other's projects: GTK has, in general, the resources needed for most of the projects which the organization chooses to implement. NGU, being a much smaller organisation, must cooperate with other organisations, nationally or internationally, in many more of its larger projects. There are, however, situations related to the project portfolios of each country in which there could be openings for utilisation of particular expertise from the other, e.g. in relation to assessment of a particular type of metal or mineral deposit or participation in development-aid projects.
4. Strategic agreements on services and skills: All but the very largest survey organisations face problems in maintaining the range of scientific support facilities or skills which they might prefer to have "in-house." Many have to resort to outsourcing, downscaling and purchase of services externally in order to resolve the dilemmas posed by their needs and priorities as against their budgets. The benefits to be accrued from long-term strategic cooperation could be important, possible ranging from more basic agreements, such as purchase of standard analytical services or access to analytical facilities, to more fundamental forms of cooperation related to scientific skills (e.g. in a purely hypothetical situation in which NGU was required to make an inventory of peat resources in Norway or, the less hypothetical situation in which GTK's expertise in mineral dressing can be a critical component in several projects being planned or considered by NGU.)
5. Opportunities for study leave and interchange such as that from which the writer has benefited.

Regional geochemical data and estimates of emissions from industry

This component in the writer's stay at GTK was based on specific problems which emerged directly and indirectly from an earlier cooperative project in which NGU and GTK had been involved, the major product from which was: Environmental Geochemical Atlas of the Central Barents Region (Reimann et al., 1998). The topics are described in one manuscript drafted prior to the writer's visit to GTK and a further manuscript which was drafted while the writer was at GTK. Both manuscripts have benefited in fundamental respects from comments and specific input from colleagues at GTK. The manuscripts are included as appendices to this report: the first is intended for submission to the journal Atmospheric Environment in the near future: the second requires further work before a decision is taken as to where it could be published.

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Rognvald Boyd
10.06.08

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Reimann, C. et al., 1998: Environmental Geochemical Atlas of the Central Barents Region. Geological Survey of Norway, 745 pp.

Appendices:

1. Emissions from the copper-nickel industry on the Kola Peninsula and at Noril'sk, Russia. Rognvald Boyd, Sarah-Jane Barnes, Patrice de Caritat, Victor A. Chekushin, Victor A. Melezhik, Clemens Reimann, Michael A. Zientek

2. Draft manuscript: The use of emission factors for estimating release of heavy metals from metallurgical processing of copper and nickel ores. Rognvald Boyd

APPENDIX 1:

Emissions from the copper-nickel industry on the Kola Peninsula and at Noril'sk, Russia

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Abstract.

Published estimates for heavy metal emissions from the copper-nickel industry on the Kola Peninsula are re-examined in the light of: a) Official Russian emission figures for 1993 and 1994, b) Modelled emissions based on calculated dry and wet deposition estimates based on data from snow and rain sampling carried out in 1994, c) Chemical data on the composition of the ores being processed by the industry. The modelled emissions, official emission figures and chemical data are mutually compatible for Ni, Cu and Co and show that previously published figures underestimated the emissions of the major elements, Ni and Cu (though within the same order of magnitude). Published figures overestimated the emissions of As, Pb, Sb and Zn by up to several orders of magnitude, in some cases exceeding the calculated total input of these metals to the plants. These conclusions have implications for estimates of emissions from the copper-nickel industries in the Noril'sk area of Siberia and from the metallurgical industry in the Urals; published estimates of these emissions have neglected information on the nature of the ores being processed (in the Urals) and on the chemistry of the ores (in both the Urals and at Noril'sk). Revised emission estimates for 1994 (the year for which observational control is available for emissions on the Kola Peninsula), using knowledge on the chemistry of the ores being processed, are proposed: taken with published information on the total emissions up to 2000 these data can give an indication of emission levels in more recent years.

Keywords: Heavy metals, nickel, copper, smelter emissions, geochemistry, ore chemistry, Russia

1. Introduction

Considerable attention has been devoted within the last forty years to the effects of heavy metal emissions from a range of anthropogenic sources on the earth's environment. The Arctic regions have been the focus of a number of major studies on regional and international scales (e.g. the Arctic Monitoring and Assessment Programme - AMAP), because of the sensitivity of the Arctic environment, including its life forms, because of transport of pollutants to the Arctic from outside the area and because of the presence in the Arctic of a number of major, point-source emitters. The Russian nickel-copper industry, with major plants at Noril'sk in Western Siberia, and at Nikel, Zapolyarniy and Monchegorsk on the Kola Peninsula (Fig. 1) is one of the most important sources of anthropogenic heavy metal emissions to the atmosphere from within the Arctic. This paper assesses information on the heavy metal emissions from the industry in the mid 1990s, a period for which direct observational information is available for the relevant parts of the Kola Peninsula. This gives a basis for conclusions, which allow a critical assessment of previous estimates of emissions.
The metallurgical industry in the cities on the Kola peninsula processes both local Ni-Cu sulphide ore, from deposits in the Pechenga Zone (the basis for the Ni-Cu industry in Nikel and Zapolyarniy), and, for certain periods, ore from deposits in the Noril'sk province in Western Siberia. Several open-pit and underground mines are in operation. Annual production in the late 1980s was estimated to be 30-35,000 tons Ni metal (Strishkov, 1989, quoted in Melezhik et al., 1994; Mining Journal 1997, 1998). Production is dominated by disseminated ore, typically containing c. 1 % Ni and 0.5 % Cu (Barnes et al., 2001).
Part of the production from deposits in the Noril'sk province in Western Siberia (which totalled c. 150, 000 t in 1996, assuming c. 30,000 t from the Pechenga area (Mining Journal 1998) was transported by sea (the only means of surface transport to and from Noril'sk) for processing in Nikel and Monchegorsk. Deposits in this province have been mined since 1935 but transport of ore to the Kola Peninsula commenced in 1971-72. Approximately 22% of the Noril'sk Nikel's total production (Mining Journal 1998) in the mid 1990s was processed by Severonickel (Monchegorsk), suggesting that transport of ore from Noril'sk was probably

equivalent to < 10,000 ton Ni metal. Collectively the Noril'sk deposits (International Mining, 2006) form a Cu-Ni resource comparable to those of the Sudbury deposits in Canada (DeYoung et al., 1985) and are one of the two largest sources of platinum metals in the world (along with the Bushveld deposits in South Africa). The Noril'sk province contains a wide range of ore types, including large volumes of massive ore, also of various types. In general the ores are characterised by having contents of Cu greater than those of Ni and by much higher contents of the platinum metals than the Pechenga ores. The Noril'sk and Pechenga ores thus have compositions as regards major metals which are quite distinct one from the other. The type of Noril'sk ore processed at Nikel and Monchegorsk in the 1990s was thought to contain, on average, 2.35% Ni and 2.7% Cu in ore with 70% sulphides (Elkem Technology, 1993).

The major metallurgical plants in the Nikel-Zapolyarniy area (Fig. 1), belonging to the Pechenganickel company (a subsidiary of Noril'sk Nickel), in addition to flotation plants, are a smelter in Nikel and a roasting plant in Zapolyarniy. The smelter processed, in the mid 1990s, ore from Noril'sk, rich Pechenga ore, concentrate produced from lower-grade local ore and pellets from the roasting plant (which processes local ore alone). The metallurgical plants in Nikel and Zapolyarniy date from the period immediately after World War II. Plans exist for modernisation of the smelter in Nikel: a new metallurgical process was being tested in 2006 (International Mining, 2006). Ni-Cu ore has been mined in the past in the Monchegorsk area (Fig. 1) but the metallurgical plants in the town, belonging to the Severonickel company (also a subsidiary of Noril'sk Nickel), processed, in the mid 1990s, pellets from Zapolyarniy, matte from Nikel and matte and ore from Noril'sk. Nickel and copper metal are refined, sulphuric acid is produced and a platinum metal- and gold-bearing sludge is sent for further processing in Krasnoyarsk in western Siberia. Cobalt was refined in Monchegorsk up until 1996 when the cobalt refinery had to be closed (Mining Journal 1997).

The Geological Surveys of Finland and Norway and Central Kola Expedition in Monchegorsk have carried out a study of the distribution of heavy metals in near-surface media (moss, humus, soil profiles) in an area extending from 24^{o}E to 35^{o}30'E and south to the Arctic Circle in Finland and to the southern border of Murmansk region in Russia (Fig. 1) (Reimann et al. 1998; http://www.ngu.no/Kola). The main aims of the project have been to study the distribution of heavy metals at regional and local scales and to distinguish anthropogenic from natural concentrations. The project area included all the major emission sources in the copper-nickel industry on the Kola Peninsula. Part of the project included modelling of total deposition of metals based on actual observational data (Caritat et al. 1997) and assessment of deposition in relation to emission figures (Chekushin et al. 1996, 1998), not least the official figures for emissions from the industry for 1993 and 1994 (Murmansk Region Committee of Ecology and Natural Resources 1995). The assessments of total deposition and emission represent significant developments in relation to previously published estimates (NILU 1984; Pacyna et al. 1985a, b; Pacyna 1995): these improvements, the main topic of this paper, are based on the above-mentioned observational data and on information on the nature and chemistry of the ores being processed.

Fig. 1: Kola Ecogeochemistry project area, showing the location of metallurgical complexes, numbered catchments studied (see also Table 3) and the area of a pilot study centred on Nikel.

2. Published emission estimates and official emission figures

2.1 Estimates based on the use of emission factors

The first estimates of emissions from the copper-nickel industry in the then Soviet Union were published in 1984 (NILU) (Table 1). The estimates are based on produced tonnage of major metallic components multiplied by emission factors. Emission factors have been described (Pacyna 1985; Nriagu & Pacyna 1988) as being based on the characteristics of the raw material and the production and pollution-control technologies employed at the source of emissions. A recent definition of emission factor is: "the amount of a given material.... generated during the consumption of a unit of raw materials .... or the production of a unit of industrial goods." (Pacyna & Pacyna, 2001). While the general nature of the copper-nickel ores being processed was well known by 1984 little was known of the trace metal chemistry of the ores and of the pollution-control technologies until the early 1990s. It is not without cause that the preface to the NILU report (1984) states: "Because of the limited information available, the users should note that the present survey may contain serious omissions and mistakes. Only experience will show to what extent these data will be of help tracing the origins of atmospheric pollutants" (The document gives specific estimates for a wide range of anthropogenic sources, not only the copper-nickel industry.)

Table 1
Estimates of metal emissions from the copper-nickel industry in the Soviet Union (t/a) (NILU 1984, Pacyna et al. 1985, Pacyna 1995 (Cu not included in the last reference)

	As	Cd	Cr	*Cu	Mn	Ni	Pb	Sb	Se	Zn	Ni/Cu
Kola	154	15	2	173	2.0	535	412	14.0	16.0	61	3.09
Noril'sk	242	24	3	312	2.5	900	650	22.0	24.9	235	2.88
Urals	462	70	5	910	5.0	585	1220	41.5	47.0	444	0.64

The data also form part of the basis for emission estimates:

- At national levels (NILU 1984; Ottar et al. 1986; Pacyna 1986a; Axenfeld et al. 1992; Pacyna 1995)
- Per unit area in Europe (Pacyna et al. 1991; Axenfeld et al. 1992; Akeredolu et al. 1994)
- At continental levels (Pacyna & Pacyna 2001)
- At global levels (Nriagu & Pacyna 1988; Pacyna 1997; AMAP 1997; AMAP 1998; AMAP 2005)
- Used in mathematically sophisticated studies of paths of transport for heavy metals within and into the Arctic (Akeredolu et al. 1994).
- Used in international conventions on emissions from industry (e.g. UN ECE Protocol on Heavy Metals (UN ECE, 1998)).

Global estimates of metal emissions to the atmosphere in 1983, i.e. in part based on the above data, have appeared in AMAP (1997). The same publication also states that: "Preliminary estimates of emissions from Severonickel are approximately 3,000 tonnes of copper and 2,700 tonnes of nickel annually, but this information needs verification". (Note that Severonickel is the name of the company running the smelter complex in Monchegorsk and Pechenganickel is the company running the activities in Nikel and Zapolyarniy: both are part of Noril'sk Nickel.) These estimates, which do not appear to include emissions from Pechenganickel in Nikel and Zapolyarniy, represent roughly 20- and 5-fold increases for copper and nickel respectively, in relation to those given in Table 1 (which do). The full AMAP scientific report (AMAP 1998) repeats the statement quoted above: in addition it states, in relation to the Pechenganickel plants: «The emissions of Cu and Ni in the Pechenganickel smelter complex are estimated to be approximately 310 and 510 tonnes, respectively. However, very recent information (e.g., Pozniakov 1993, Lyangusova 1990) suggests that actual emissions could be about one order of magnitude higher. By contrast, the official Russian data place the 1994 emissions from Nickel and Zapolyarniy at about 163 tonnes of Cu and 297 tonnes of Ni (CENR 1995)". The effect of the quotations from the two AMAP documents is to imply, without stating categorically, that there is reason to doubt the official Russian figures. The data from NILU (1984) form the basis for a figure in AMAP (1998) showing emissions of As, Cd, Ni and Zn from various sources in the former Soviet Union though with an apparent upward adjustment of the emissions from e.g. Noril'sk in relation to the estimates quoted in Table 1. A further figure in AMAP (1998) indicates emissions of Pb of the order of 800 tonnes annually from the Noril'sk smelters, based on estimates in Pacyna (1993) (also a significant increase relative to the estimate in NILU (1984).

Pacyna (in AMAP, 2002) quoted official Russian emission figures for the plants on the Kola Peninsula for 1994 (Murmansk Region Committeee of Ecology and Natural Resources, 1995), (see Table 2), without any comment on the discrepancies between these figures and those based on the use of emission factors presented in numerous earlier publications. In the same publication, again without comment in relation to conclusions in previous work (Pacyna et al., 1984; Akeredolu et al., 1994; Pacyna 1994), he writes "The majority of these emissions deposit within the emission region.", while in the next sentence stating "Asian sources are expected to become more significant for the High Arctic than sources in the Russian Arctic."

2.2 Official emission figures

Official figures for the release of base metals to the atmosphere from the copper-nickel industries on the Kola Peninsula and at Noril'sk are shown in Table 2. These figures broadly reflect the compositions of the ores being processed in the different plants. The Zapolyarniy emissions have a Ni:Cu ratio similar to that found in Pechenga ore. The Nikel and Monchegorsk emissions reflect the blend of ores from both Pechenga and Noril'sk being processed, in that both have show lower Ni:Cu ratios than Zapolyarniy. Further evidence documenting the close correlation between the chemistry of emissions and that of the ore feed is provided by data on the platinum metal chemistry of soils around Monchegorsk, which matches that of ores from the Talnakh deposits at Noril'sk with a «low» content of Cu rather closely (Boyd et al. 1997). The emissions from Noril'sk have the lowest Ni:Cu ratio, reflecting the higher grade of Cu than Ni, even in the ore types poorer in Cu (see Table 5): the sulphur dioxide emissions at Noril'sk are due to the predominance of massive ores as opposed to the lower-grade disseminated ores which dominate production from the Pechenga ore bodies, leading to relatively low sulphur dioxide emissions from Zapolyarniy..

Table 2

Official figures for metal emissions in 1994 from the Ni-Cu industry on the Kola Peninsula (Murmansk Region Committee of Ecology and Natural Resources (1995), quoted in Reimann et al., 1997) and for Ni, Cu and SO_2 from the Noril'sk plants (Surnin et al. 1997) The figure for Co emission from Noril'sk is for 1992 (MGO Review 1993), a year in which the nickel emissions were at a level similar to that in 1994.

	Ni	**Cu**	**Co**	**SO_2**	**Ni/Cu**
Nikel	136	82	5,2	129 000	1.66
Zapolyarniy	161	81	5,4	69 000	1.99
Monchegorsk	1 619	934	81,5	98 000	1.73
Total Kola Ni-Cu industry	**1 916**	**1 097**	**92,1**	**296 000**	1.75
Noril'sk	**1 280**	**2 380**	**67,5**	**1 860 000**	0.54

It is inexplicable, especially in view of the statements quoted in AMAP (1997,1998) and the fact that Pacyna and Pacyna (2001) refer to Boyd et al. (1998), in which the above table appears, that these authors, in the paper indicated, state that total emissions from primary "copper and nickel production" (text, p. 279) or, alternatively "copper production" (heading, Table 5) in Europe in 1995 were 555 t Cu and 277 t Ni. The official Russian figures indicate that the plants on the Kola Peninsula emit four times the tonnage indicated by Pacyna and Pacyna (2001) for the whole of Europe.

Systematic official information is available (Ekimov et al. 2001) for the development of certain aspects of the emissions from the industry in the period 1998-2000. These data indicate a reduction of 33% in SO_2 emissions from the Kola plants and an increase of 11% in SO_2 emissions from Noril'sk, but do not permit deduction of values for specific metals. Limited information is available on emissions from Ni production in the Urals (Ekimov et al. 2001): it confirms information discussed below, that the nickel ores in the Urals are nickel-cobalt laterites, with a quite different chemistry from the sulphide ores exploited on the Kola Peninsula and at Noril'sk. Ekimov et al. (2001) indicate that the total tonnage of emissions to the atmosphere from metallurgical processing of nickel ores in the Urals in 2000 was 196,000t, 10% lower than that at the plants on the Kola Peninsula, with major components of SO_2 and CO_2. The level of emissions was partly due to a doubling of production in 1999. The tonnage of emissions is, of course, also heavily influenced by the efficiency of the different plants from which they emanate, including in the cases of Monchegorsk and Noril’sk several individual point sources. Given the difference in the tonnages produced (see below) it appears that the Noril’sk plants have a much more efficient metal recovery than that at Monchegorsk.

2.3 Evidence from models of deposition

De Caritat et al (1997) have modelled total loadings of Ni, Cu and Co within circles of varying radius around Monchegorsk, on the basis of data on the chemistry of annual precipitation (water soluble and particulate) within catchments close to the city. The calculated loadings are compatible with (within 10% of) the official emission figures for Ni and Co, assuming a «shadow» zone around the source of 200-300 m. The calculated loading for Cu is c. 65% of the official figure, for the same order of «shadow» zone.
Chekushin et al (1998) have calculated deposition/km^2 for eight catchments on the Kola Peninsula, at varying distances from the sources of industrial pollution. Data for calculated deposition/km^2 for catchment 2 (5 km S of the smelters in Monchegorsk) (see Fig. 1) and catchment 1 (10 km NE of the roasting plant at Zapolyarniy) are given in Table 3.

Table 3

Calculated annual deposition/km^2 in kg in catchments 1 and 2 for selected elements

(Chekushin et al. 1998).

	As	Cd	Cr	Cu	Ni	Pb	Sb	Co	V	Ni/Cu
Catchment 1	2.7	0.2	12	183	434	1.5	0.6	16.3	4.2	2.37
Catchment 2	2.8	0.4	5,2	494	845	5.8	0.7	60.3	19.3	1.71

These data show that the calculated depositions of Cu, Ni and Co are in the general proportions found in the official emission figures. Calculated depositions of As, Cr and Pb are two orders of magnitude lower than those of Cu and Ni and those of Cd and Sb three orders of magnitude lower. V emissions are 1-2 orders of magnitude lower than those of Ni and Cu. These data thus form a basis for estimating emissions of the trace metals (see below).

3. The ore deposits and their chemistry

3.1 Pechenga

As noted above the deposits mined in both the Kola Peninsula and the Noril'sk area are copper-nickel sulphide deposits. General descriptions of the ore bodies have been published in a number of English-language publications (e.g. Smirnov 1977, Gorbunov et al. 1985) but little chemical data was released prior to the 1990s, especially as regards trace constituents. Smirnov (1977) included information on the proportions of nickel:copper:cobalt in the different ore types. Naldrett (1981) published values for the content of Ni, Cu, Pt, Pd and Au in Pechenga ore, recalculated to total sulphide, based on data from Gorbunov (1968): the figures presented suggest a Ni/Cu ratio of just under 2 and a total platinum metal content in average ore of less than 1 ppm. Melezhik et al. (1994) give general chemical information on the different ore types and their host rocks. Representative data for the major- and trace-element constituents of important ore types in the Pechenga area are shown in Table 4.

Table 4
Chemical data in ppm for forty samples of Pechenga ore (based on data set used in Barnes et al. 2001), grouped into weak dissemination (WD), rich dissemination (RD), brecciated massive ore (BM) and massive ore (M). n is the number of samples in each grouping. Correlation coefficients are shown below, with grey shading for those with a positive correlation to Ni.

	n	Ni	Cu	S	As	Cr	Pb	Sb	Se	Zn	Co
WD	11	8 300	4 000	38 600	7,9	2 038	1,05	1,07	5,0	230	257

RD	8	37 200	10 900	135 400	10,0	1 196	3,30	1,12	32,3	257	704
BM	10	33 000	5 700	178 700	41,1	966	3,44	0,60	32,3	230	794
M	11	71 100	11 600	287 500	32,7	154	3,21	0,70	57,3	204	1 516

Ni			0,846	0,969	0,538	-0,976	0,701	-0,515	0,989	-0,526	0,989
Cu				0,711	0,086	-0,749	0,658	-0,023	0,825	-0,063	0,760
S					0,729	-0,998	0,751	-0,707	0,983	-0,594	0,988
As						-0,704	0,629	-0,990	0,618	-0,562	0,630
Cr							-0,783	0,674	-0,992	0,541	-0,985
Pb								-0,525	0,795	0,039	0,672
Sb									-0,580	0,659	-0,620
Se										-0,468	0,981
Zn											-0,627

International Mining (2006) describes plans for development of underground mining to replace then current production from a major open pit, the Tsentralny mine: reserves for one of the four major deposits in the region of Nikel and Zapolyarniy are given as 160,337,000 tons carrying 0.67% Ni and 0.31% Cu (close to the Ni:Cu ratio for "Weak dissemination" in Table 4. The paper does not include data on the contents of cobalt, platinum metals or other trace metals in the reserves.

3.2 Urals

No significant copper-nickel sulphide deposits are known in the Urals (Voplkov 2003; Herrington et al., 2005). A wide range of deposits formed by various types of deep weathering of nickel-cobalt-bearing silicates in different geological environments is, however, found in the southern Urals (Herrington et al., 2005; Freysinnet et al. 2005, and other authors quoted therein). A minor tonnage of nickel has been produced from these (Mining Journal 1997). Ekimov et al (2001) indicated that production was increased in the late 1990s. These ores have a bulk chemistry dominated by hydrous silicates and oxides which is completely different from that found in the sulphide ores in the Pechenga and Noril’sk areas. The ores are dominated by secondary iron, magnesium and aluminium silicates in which the metals of economic interest are Ni and Co, generally of the order of 1 - 1.5% Ni and less than 0.1% Co. No information has been found on the contents of other trace metals in these ores but the literature on other deposits of this type, e.g. Golightly (1981) suggests that oxides of Cr and Mn are probable trace components in amounts under 0.5%. BRGM (2003) and Volkopv (2004) document the presence of major deposits of Cu and Cu-Zn (also described in a range of earlier publications, including Smirnov (1977). Volkov

(2004) indicated that eight Cu deposits, of which five with high grades of Zn were in production in 1998: he implies that all these deposits had been in production since the Soviet period. The BRGM (2003) study includes assessment of the environmental impact of a number of metallurgical complexes, including the copper smelter complex at Karabash (Liestel et al. 2003), which is quoted as having high emissions of Pb, Cd, As and SO_2. Ores of these types do not contain notable quantities of Ni.

3.3 Noril'sk

The Noril'sk ore province contains two main groups of deposits, Noril'sk s.s. at which many of the deposits are worked out, and Talnakh, the latter being the focus of production at present. Scanty information on the chemistry of the economically interesting components in the ores was published in the west in the 1970s (Naldrett & Cabri 1976; Smirnov 1977; Hoffman et al. 1979), indicating that the ores were rich, containing several per cent each of Ni and Cu, with Cu>Ni, and with unusually high contents of platinum metals, especially palladium. Numerous publications in the 1990s resulted from major cooperative projects involving Russian geologists and groups from the USA, Canada and other countries (among others Arndt et al. 2003, 2005; Czamanske et al. 1992, 1994, 2002; Naldrett et al. 1996; Zientek et al. 1994). Most of the papers focus on the chemistry of the ores (with emphasis on Ni, Cu and the platinum group elements) or their host rocks based on representative samples collected during the projects, but Czamanske et al. (1992), Zientek et al. (1994) and Foose et al. (1995) include data on the contents of other trace metals in the ores. Comprehensive data on the reserves available at several deposits in the Noril'sk camp were presented in International Mining (2006). "Total proved and probable reserves" in the Noril'sk camp were stated to be 318,345,000 t at 1.63% Ni, 2.79% Cu and 7.98 g/t (Pt + Pd + Au) (over 1.4 billion tons of ore at lower grades, i.e. excluding reserves, was classified as "Measured and indicated resources"): this source does not contain data on Co or trace metals without economic interest.

Table 5
Chemistry of the main ore types at Oktyabrsky mine at Talnakh in the Noril'sk camp. The figures are based on a graphical presentation in Zientek et al. (1994). Ni, Cu and S are in weight percent and the trace metals in ppm. Se figures are from Czamanske et al. (1992) and show levels found in ores with a Cu content corresponding to the ore types defined by Zientek et al. (1994).

	Ni	Cu	SO_2	As	Pb	Sb	Se	Zn	Co
Noril'sk Cu-rich ore	2,5	27,0	32,5	1,5	200	1,00	100 - 300	600	800

Noril'sk Cu-poor ore	3,3	4,2	31,2	0,3	20	0,15	c. 50	150	1 500

Various lines of evidence, including the official emission figures, calculated deposition figures and others (Elkem Technology 1993) suggest that the ore transported from Noril’sk to Nikel and Monchegorsk for processing is of the Cu-poor type.

4. Annual production in the industry

4.1 Pechenga

Little is known of the exact proportions of the different ore types being produced and none on their historical production. It is, however, known that the bulk of production in the 1990s was from lower-grade disseminated ore being mined in the large open-pit facilities near Zapolyarniy. Reserves are, however, considerable: International Mining (2006) indicates reserves of 160,000,000 tons grading 0.67% Ni and 0.59% Cu in the Zhdanovskoye deposit alone and states that metallurgical testing was then proceeding with a view to modernisation of the plant at Nikel.

The data in Table 4 suggest that a figure for production of Ni metal can be used as a basis for estimation of the tonnages of Cu, As, S, Pb, Se and Co being processed (i.e. input to the plant), independent of the proportions of the different ore types processed. Cr has a strong negative correlation with these elements and Sb and Zn more moderate negative correlations with Ni and substantially no correlation with Cu. Cr, Sb and Zn have moderately positive correlations, one with the other, indicating their presence largely in silicates or oxides. Tonnages of Cr, Sb and Zn being processed can thus only be estimated on the basis of quite detailed knowledge of the chemistry of a given tonnage of ore.

Annual production, as noted above, was estimated to be 30-35,000 tons Ni metal in the late 1980s (Strishkov, 1989, quoted in Melezhik et al., 1994). Assuming the lower value this implies, using the proportions of the metals in the low-grade dissemination, a production of the order of 15,000 tons Cu metal and 950 tons Co metal from local ore. The input of the trace metals would, assuming the compositions in Table 4, be approximately as shown in Table 6.

Little is known of the tonnage of nickel produced from the laterites in the Urals: Dalvi et al. (2004) estimate that the Ni production from two operations, Ufaley and Yuzural, is 20,000t/a.

4.2 Noril'sk

Russia’s total mine output of nickel was c. 180,000 tons in 1996 (Mining Journal 1998). Given the level of production indicated above from the Pechenga area this implies that production from Noril’sk was just over 150,000 tons, implying a copper production of c. 260,000 tons and c. 3,000 tons of cobalt (using ratios given in Mining Journal (1997). The production figures for nickel and copper can result from mixes of a wide range of different ore types but if the two sets of data shown in Table 5 are taken as end-members then the metal produced could be modelled as resulting from production of c. 400,000 tons of Cu-rich ore and just over 4 million tons of Cu-poor ore. Whatever the true figures, "Cu-poor" ore must dominate production completely. (It should be noted that the figure for SO_2 emissions from Noril’sk given in Table 2 would indicate a higher total production, minimum c. 5.5 million t, suggesting that the metal contents used in Table 5 may be too high: this is confirmed by the data given in International Mining (2006) but the latter source does not give trace element data, other than for Pt, Pd and Au.) Given the above, hypothetical mix of Cu-rich and Cu-poor ores, the input of selected trace metals would be approximately as shown in Table 6.

Table 6
Input of certain trace metals (in tons) from the Pechenga and Noril’sk ores, based on the known production of nickel in 1996 and the ore compositions shown in Tables 4 and 5.

	As	Cr	Pb	Sb	Se	Zn
Pechenga	33,0	8 600	4,5	4,5	21	970
Noril'sk	1,8	n.a.	160,0	1,0	280	840

5. Assessment of the emission estimates in relation to ore type, chemistry and processed tonnage

5.1 Pechenga

Comparison between the official emission figures (Murmansk CERN 1995) and the data on the chemistry of the Pechenga ores in Table 4 shows that there is an exact correspondence

between the proportions of Ni:Cu:Co in the emissions from Zapolyarniy and the proportions of the same metals in weak disseminated ore. This is what would be expected, given that this is the ore type thought to be dominant in current production in the area and given that the only ores processed in Zapolyarniy are of local origin. The emissions from Nikel have higher proportions of Cu:Ni and S:Ni which is, again, as would be expected, given that ores from Noril'sk with higher ratios of Cu:Ni and S:Ni are smelted at Nikel as well as local ores.
As already noted modelled loadings of Ni and Co within circles of varying radius around Monchegorsk, on the basis of data on the chemistry of annual precipitation (water soluble and particulate) are compatible with (within 10% of) the official emission figures. Many factors influence the nature of deposition of emissions from the Ni-Cu plants - water solubility v. particulate character, particle size and density, etc. Given these provisos the depositions calculated/unit area (Table 3) are compatible with the ore chemistry shown in Table 4, for elements available in both sets of data. The main «anomaly» is the low calculated deposition of Cr, which is easily explained, as Cr is not sulphide-bound and would thus not be emitted to the same extent as the sulphide-bound elements.
The above lines of evidence suggest an overall compatibility between ore chemistry, official emission figures and calculated loadings and deposition rates based on comprehensive observational data. Collectively, these data have the following implications for the emission estimates based on the use of emission factors (NILU 1984, Pacyna et al. 1985, Pacyna 1995):

- Emissions of Cu and Ni were underestimated by factors of 4-6.
- The postulated emissions of As, Pb and Sb exceed the total input of these metals to the plants by factors of at least 5 for As, 25 for Pb (taking account of the fact that a limited amount of relatively Pb-rich ore from Noril'sk is processed in Nikel and Monchegorsk) and 3 for Sb.
- The estimated emission of Se is close to the calculated input and is probably also too high.

Several of these conclusions have been supported by other studies:

- Pb concentrations in samples of European feather moss collected in 1995 (Rühling and Steinnes 1998; Ford et al. in AMAP (2005) show clear anomalies for Cu and Ni in the region of the smelter complexes on the Kola Peninsula, but are at background level for Pb, indicating that Pb is not a major component in the emissions from the smelters.
- As part of the Barents Ecogeochemistry Project samples of European feather moss were also collected in 2000 (Salminen et al., 2004): these samples also showed clear anomalies for Cu and Ni in the region of the smelter complexes on the Kola Peninsula, but

background level for Pb, again indicating that Pb is not a major component in the emissions from the smelters: the same applies to Zn.

- Stebel et al. (2007) report measurements of deposition from several locations in Norway and Finland, close to the smelter at Nikel in 2004 and 2005. These show levels of Ni, Cu, Co and As, which are compatible with the smelter being the source: Pb and Zn values at the site closest to the smelter (Svanvik) are respectively 3-4% and 10-20% of those of Ni. The location most remote from the smelters shows Pb deposition double that of Ni, and Zn values an order of magnitude greater than that of Ni. The presence of a more regional source or, of processes leading to elevated deposition of Pb and Zn indicates that part of the deposition of these metals at Svanvik (and at Nikel) may be unrelated to the smelter.

Similar weaknesses in the application of emission factors by Nriagu & Pacyna (1988) and EMEP/CORINAIR (1995) have been documented by Skeaff & Dubreuil (1995) for non-ferrous metal smelters in Canada: they showed that emission factors based on actual observational data were between 40% and 0.066% of the emission factors applied by the former authors to emissions of most trace metal emissions from most types of smelter. Despite this Pacyna and Pacyna (2001) dismiss the emission factors advocated by Skeaff & Dubreuil (1995), stating: "the estimates presented in this paper are claimed to be more accurate than those used by Skeaff and Dubrueil (1995)." The exceptional cases, in which there was approximate accord, are for Cd and Hg emissions from lead production and Sb emissions from Zn production.

5.2 Urals

The estimates of emissions from «copper-nickel production» in the Urals based on the use of emission factors (NILU 1984, Pacyna et al. 1985, Pacyna 1995) cannot be related to copper-nickel deposits as such, as deposits of this type have not been in production in the Urals for many decades. As noted above, the nickel deposits in the Urals which are in production are of a completely different type and have a much lower level of production. Copper, lead and zinc are produced in the Urals but from deposits of completely different types from those being considered here. The estimated emission of Ni is almost certainly much too large, while the figures for the other metals should be reassessed in relation to the chemistry of the ore types in production and other relevant factors.

A relatively recent study in the vicinity of the Cu smelter town of Karabash, near Chelyabinsk (Williamson et al. 2003) shows high emissions of S, Pb, Cu, Sn and Zn (but not apparently of Ni). This is compatible with knowledge of the ores being processed.

5.3 Noril'sk

Published emission figures for 1994 and chemical data presented above allow the following assessment of the emission estimates based on the use of emission factors (NILU 1984, Pacyna et al. 1985, Pacyna 1995):

- Emissions of Cu and Ni were underestimated by factors of 8 and 1.5 respectively.
- The postulated emissions of As, Pb and Sb exceed the total input of these metals to the plants by factors of c. 100, 4 and 22 respectively.

6. Revised emission assessment

The consistent picture given by ore chemistry, official emission figures and calculated loadings and deposition rates for the plants on the Kola Peninsula indicates that the emissions of trace metals can be estimated using their ratios relative to nickel in the calculated deposition figures (Table 3) and applying these to the emissions of Ni or Cu. Ideally one would consider the three sources on the Kola peninsula separately but given the dominance of emissions from Monchegorsk in relation to the total emissions from the three sources and the uncertainties intrinsic in the estimates, the figures given below are based on the ratios of the trace metals to nickel in the depositions calculated for Catchment 2 (Table 3), close to Monchegorsk, applied to the total emission of Ni from the three centres (1,916 t, Table 2). This method suggests emissions of the order of 6.3 t As, 0.9 t Cd, 11.8 t Cr, 13 t Pb, 1.6 t Sb and 43.7 t V from the Ni:Cu industry on the Kola peninsula as a whole (Table 7). Interestingly the official emission figure for V_2O_5 from the industry is 94 t (Murmansk CENR 1995), corresponding to 52 t V. The figure for Pb is of the same order as the total input of Pb to the Kola plants, assuming the figures in Table 6 and that 6-7% of the Pb-rich production from Noril'sk is processed on the Kola peninsula: it may also be assumed that a part of the Pb deposition calculated for catchment 2 is due to other sources (vehicle traffic), suggesting that this might also be the case for the estimate of 13 t. Use of the annual deposition calculated for

Zn (Chekushin et al. 1995) in Catchment 2 in the manner used for the elements considered above leads to an estimated Zn emission of 27 t.

No observational data of the type shown in Table 3 are available for the Noril'sk area. As already indicated the published emission figures (Surnin et al. 1997), viewed in relation to the production of Ni and Cu, suggest that the Noril'sk plants have a more efficient recovery of metals than those on the Kola Peninsula. Applying the ratios modelled emission:modelled input found for the metals emitted from the plants on the Kola Peninsula to the input of the same metals at Noril'sk, should give a maximum estimate of the emissions of these metals at Noril'sk. For the metals for which the relevant data are available this leads to estimates of < 1 t As, 150 t Pb, < 1 t Sb and 29 t Zn (Table 7). These figures must be viewed as tentative.

Table 7

Published emission figures (1994) for the major metals and SO_2 (from Table 2) and estimates of emissions of trace metals based on sources and methods described above. NB: the estimates of trace metal emissions from the Kola area have a much higher reliability than those for Noril'sk (n.a. = not available).

	Ni	Cu	Co	SO_2	As	Cd	Cr	Pb	Sb	V	Zn
Kola	1 916	1 097	92.1	296 000	6.3	0.9	11.8	13	1.6	43.7	27
Noril'sk	1 280	2 380	67.5	1 860 000	<1	n.a.	n.a.	150	<1	n.a.	29

7. Status at 2000 and later

Official emission figures for 2000 (Ekimov et al. 2001) indicate a reduction of SO_2 emissions from the plants on the Kola Peninsula by c. 33%. Plans for modernising these plants have not so far been implemented, which suggests that the figures given above for 1994, adjusted in relation to production levels, are relevant as a guideline for metal emission levels in 2000. The same source indicates an increase in emissions from the Noril'sk plants in 2000 by c. 15% relative to 1994 levels.

Barcan (2002) has presented detailed data for emissions of SO_2, Ni, Cu and Co for the Severonickel plants in Monchegorsk up to 2001. His paper gives a comprehensive picture of the mineralogical and chemical nature of components released from different processes. The data are compatible with those of Ekimov et al. (2001) (with some suppositions in relation to emissions at Nikel and Zapolyarniy) but are difficult to project to the other plants on the Kola Peninsula because of the differences in feed to the plants and processes in them. He indicates that SO_2, Ni, Cu and Co emissions in Monchegorsk in 2001 were respectively 44,000, 1,212, 827 and 44 tons.

Pacyna et al. (2007) present an analysis of heavy metal emissions from various sectors in Europe, based on results from the ESPREME project. Their figures for emissions from non-ferrous metal production in Europe as a whole are: 132t As, 52t Cd, 54t Cr, 49t Ni and 1471t Pb. The figure for Ni is 4.35% of the figure given by Barcan (2002) for Ni emissions from the Severonickel smelter complex in Monchegorsk alone, and is incompatible with the information presented above on pollution levels in relation to production in the 1990s, especially in the absence of significant modernisation of the metallurgical plants on the Kola Peninsula. The ESPREME database (http://espreme.ier.uni-stuttgart.de), to which reference is made by Pacyna et al. (2007), indicates that emissions from the non-ferrous metal industry in Russia in 2000 were 5.0t. Neither the publication nor the database includes values for emissions of Cu and Co. A further curious fact is that Pacyna et al. (2007) show a map of spatial distribution of As emissions in Europe in 2000, on which all the grid cells on the Kola Peninsula are at background level (emissions < 0.25t per unit area of 50 x 50 km^2): this is incompatible with several lines of evidence presented above, even when considering possible changes in production levels from 1995 to 2000.

8. Conclusions

Previously published estimates of metal emissions from the Ni-Cu industry in Russia suffered from significant deficiencies, emissions having been seriously underestimated for Ni and Cu and even more seriously overestimated for As, Pb, Sb and Zn. Some of the weaknesses can be understood and were undoubtedly the reason for the note of caution sounded in the original reference (NILU 1984), a caution which has been sporadic in subsequent use of the data. Part of the difficulty in assessing the figures published in numerous later papers lies in the absence of detailed explanations of how revisions of the original estimates have been made. Application of knowledge of the nature and chemistry of the ores being processed would have strengthened the estimates, in particular removing misconceptions about emissions from the metallurgical industry in the Urals immediately and adjusting the figures for the Ni-Cu industry on the Kola Peninsula and at Noril'sk as more ore-chemical data, official emission figures and relevant observational data have become available. Geological data available in English as early as Smirnov (1977) makes it clear that the Cu ores being processed in the Urals are not Ni-Cu sulphide bodies, and thus have a quite different chemistry.

This paper has focused on emissions from processing of Ni-Cu ores in Russia. Several of the sources of emission estimates based on emission factors quoted above, e.g. NILU (1984), Nriagu and Pacyna (1988), Pacyna (1995) present estimates of emissions from other metallurgical and mineral-based industries in the former Soviet Union, in other regions or for the whole globe in the case of Nriagu and Pacyna (1988). There is a strong case for a re-assessment of all emission estimates given for other metallurgical and mineral-based industries: such a re-assessment should involve:

- The use of basic geological knowledge about the raw materials used in the industries.
- The use of modern data on the chemistry and mineralogy of the raw materials.
- Knowledge of the metallurgical processes and emission abatement technologies being used, where available.
- The application of relevant observational data where available.

Any of these elements would result in significant improvements to the previously published estimates based on the use of emission factors.

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APPENDIX 2

Draft manuscript: The use of emission factors for estimating release of heavy metals from metallurgical processing of copper and nickel ores

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Abstract

Emission factors related to trace metal release from smelting of Cu and Cu-Ni ores and estimates of emissions based on these are re-assessed using basic knowledge on the chemistry of the raw materials being processed. Estimates which are established in the literature have errors at the level of orders of magnitude for certain metals, in some cases too high and in other cases, too low. The metal emissions from these sources have a considerable, but local impact, generally within a radius of 50-200 km, unlike certain source categories which are related to population density or to biomass burning, impact factors on a continental scale.

1. Introduction

Emission factors have been in use in environmental science since the early 1980s (Pacyna, 1982; NILU, 1984; Pacyna, 1986a), as a means of estimating heavy metal emissions from high-temperature industrial processes in the absence of observational data. Results based on the use of emission factors have been used in compilations of emissions:

- At the level of individual nations or regions within them (NILU 1984; Ottar et al. 1986; Pacyna et al., 1985; Pacyna 1986a; Axenfeld et al. 1992; Pacyna 1995)
- At European level (Pacyna et al., 1984; Pacyna, 1987; Pacyna and Graedel, 1995; Pacyna, 1998; Pacyna et al. 2007)
- Per unit area in Europe (Pacyna et al. 1991; Axenfeld et al. 1992; Akeredolu et al. 1994)
- At a continental level (not only Europe) (Pacyna, 1998; Pacyna and Pacyna 2001)
- At global levels (Pacyna 1986b;Nriagu & Pacyna 1988; Pacyna 1997; AMAP 1997; AMAP 1998; AMAP 2005)
- In mathematically sophisticated studies of paths of transport for heavy metals within and into the Arctic (Akeredolu et al. 1994).
- Of specific metals: Hg (Pacyna and Pacyna, 2002; Pacyna et al., 2006)
- In international conventions on emissions from industry (e.g. UN ECE Protocol on Heavy Metals (UN ECE, 1998)).

Nriagu and Pacyna (1988) state that the emission factors which they present are determined by: 1) "the concentration of the trace elements in the raw material; 2) the production technology employed… and 3) the type and efficiency of the pollution control installations." Whether expressed explicitly or not, these qualifications apply to all estimates based on the use of emission factors, not only those relating to emissions from processing of metallic ores. The qualifications also indicate that estimates of emissions, in the absence of direct observational data, should, in the case of ore beneficiation and primary metallurgical processes, build on knowledge of the chemistry of the raw materials (i.e. geology) and of the processes applied to them (i.e. metallurgy). The situation is further complicated by the fact that while most countries which are major producers of, e.g. copper, have their ownsmelter capacity there are also three countries which have minor/no mine production of copper but which smelt imported copper ore: these are Japan, Korea and Germany (Goonan, 2004; British Geological Survey, 2007). Several countries, which are not significant producers of nickel ore, have smelting and/or refinery capacity, e.g. Japan and Norway (British Geological Survey, 2007). This paper will concern itself with results achieved and published by application of emission factors in assessing release of heavy metals to the atmosphere from smelting of copper and nickel ores, with particular emphasis on the implications of the nature and composition of the ores being processed.

2. Previous work

There is a significant body of literature in which the assessments of total anthropogenic emissions published by e.g. Nriagu and Pacyna (1988) and their importance relative to natural emissions (Nriagu, 1989) have been thoroughly examined (e.g. Geological Survey of Canada (1995), Rasmussen (1996, 1998), Richardson et al. (2001). There is also a large body of literature in which the emissions from specific metallurgical plants are documented and their impact analysed from a geochemical or ecological viewpoint. Much of this literature focuses on only a few industrial centres, e.g. those on the Kola Peninsula in NW Russia (e.g. Reimann et al. (1997a,b, 1998), Kashulina et al. (2003), Barcan et al. (1998), Barcan (2002), and certain smelters in Canada (e.g. Henderson et al (1998), Henderson et al (2002), Doyle et al. (2003), Savard et al. (2006), Zdanowicz et al. (2006), while most others are weakly documented, if at all. There have, however, been few attempts to assess the implications of the use of emission factors in relation to the metallurgical industry from the perspectives of metallurgy, i.e. how the materials are processed, or geology, i.e. knowledge of the raw materials.

Skeaff and Dubrueil (1997) employed publicly available data for emissions of ten metals from the primary non-ferrous smelting industry in Canada, with data on metal production, to calculate emission factors for these metals for 1993: their results were, in most cases, between c. 40% and 0.066% of emission factors found in the literature (median of the ranges provided by Nriagu and Pacyna (1988)): this work found much better correspondence between the calculated emission factors and the range indicated by EMEP/CORINAIR (1995) where this source provided emission factors for the metals concerned.

Boyd et al. (1998, submitted) demonstrate how estimates of emissions from the copper-nickel industry in Russia has been used in a wide range of publications, e.g. NILU (1984), Pacyna et al. (1985), Pacyna (1995, 1998) without recognition of the implications of the nature of the ores and without due recognition of official Russian figures on emissions. The collective term "copper-nickel" production used in the above-mentioned publications conceals a range of different types of ore, each with distinct chemical characteristics. It is thus misleading to apply the same emission factors to processing of nickel-cobalt laterites found in the Urals as to processing of the nickel-copper sulphides exploited at Noril'sk and on the Kola Peninsula. The latter, though belonging to the same general group of ore types, are also quite distinct: the Noril'sk ores have much higher contents of Cu than of Ni, a factor which does not appear to have been recognized by, e.g. NILU (1984) or by Pacyna (1998). The copper ores being processed at smelters in the Urals belong to several different types, none of them with the chemical characteristics of the nickel-copper sulphides exploited at Noril'sk and on the Kola Peninsula.

The opening of cooperation with scientific organisations in Russia and the possibility of access to important Russian ore deposits led to a large volume of literature on these deposits, published from the early 1990s onwards (e.g. Czamanske et al., 1992, 1994; Naldrett et al., 1992; Zientek et al., 1994). Taken with publicly available production data it is possible to estimate the input to the plants of trace metals for which analytical data in the ore is available (Boyd et al., 1998, submitted). These calculations have shown that emission estimates published by NILU (1984) and other listed publications up to, and including Pacyna (1998), exceed calculated input to the plants on the Kola Peninsula by factors of at least 5 for As, 25 for Pb, and 3 for Sb. More surprisingly Pacyna (1998) seriously underestimates the emissions of the major metals, Ni and Cu (Murmansk CENR, 1995 quoted in Reimann et al., 1997a), which have, in the case of the plants on the Kola Peninsula, been confirmed by independent evidence on deposition (Chekushin et al., 1996, 1998).

3. Development of emission factors

Emission factors have been described (Pacyna 1985; Nriagu & Pacyna 1988) as being based on the characteristics of the raw material and the production and pollution-control technologies employed at the source of emissions. A recent definition of emission factor is: "the amount of a given material.... generated during the consumption of a unit of raw materials .... or the production of a unit of industrial goods." (Pacyna and Pacyna, 2001). Tables for emission factors relating to non-ferrous metal production have been published by Pacyna (1986), Nriagu and Pacyna (1988), Pacyna and Pacyna (2001) and, in the case of Pacyna (1998), using a table showing ranges of emission factors applied to various branches of the metallurgical industry in Europe (some of the ranges covering two orders of magnitude). The emission factors and calculated emissions are portrayed in relation to separation of the non-ferrous metallurgical industry into two or three branches: copper-nickel and lead-zinc production as in NILU (1984), copper-nickel, lead and zinc-cadmium production as in Nriagu and Pacyna (1988) or copper-nickel, lead and zinc production as in Pacyna (1998) and Pacyna and Pacyna (2001). In NILU (1984) it is specified that the emission factors are applied in g/t Cu produced, except for that for Ni, which is applied to g/t

Ni produced. The latter qualification is repeated in Pacyna (1985), but not in Nriagu and Pacyna (1988).

Table 1 shows the development of published emission factors from 1981 to the present. The only figures which are calculated on the basis of reported emissions (Skeaff and Dubreuil (1997) are also the only ones which are specifically related to processing of Cu and Cu-Ni ores. Skeaff and Dubreuil (1997) compare their emission factors with those of EMEP/CORINAIR (1995) and consider that they correspond "reasonably well" in relation to Cu and Ni production.

Table 1

Emission factors in grams/tonne from primary smelter production of copper and nickel. *: the figure for Ni is from Schmidt and Andren, 1980); **: the emission factor is stated in g/ton Ni produced; ***: the emission factors are shown in Pacyna (1998) as a bar diagram ***(check Axenfeld!!;)***[#]: Europe, N. America and Australia; [##]: Africa, Asia, S. America.

	As	Cd	Cu	Mn	Ni	Pb	Sb	Sn	Se	V	Zn
Pacyna (1981, 1986)*	1000	-	1700-3600	-	*9000	2300-3600	100	-	-	-	970
NILU (1984)*	1000	200	2500	-	**9000	2950	100	-	113	-	845
Nriagu & Pacyna (1988)*	1000-1500	200-400	1700-3600	100-500	900	1300-2600	50-200	50-200	50-150	5-10	500-1000
Axenfeld (1992), Pacyna (1998)***	2-2000	0.5-130	-	-	-	20-2000	-	-	-	-	300-1050
EMEP/CORINAIR (1995) Ni	>500	200-500	1500	100-500	>900	50-250	50-200	-	50-150	-	>500
EMEP/CORINAIR (1995) Cu	15-50	3-10	200-300		10-100	>1000	10-20	-	10-20	-	100-200
Skeaff and Dubrueil (1997)	91.2	56.7	781	0.2	631	827	1.5	-	3.7	-	316
Pacyna & Pacyna (2001) [#]	100	50	300	1	150	300	10	10	10	5	200
Pacyna & Pacyna (2001) [##]	500	200	3000	10	1500	1000	50	50	50	10	500

Pacyna (1998) provides ranges for only four of the metals shown in the table above: these overlap, for As and Zn, the ranges of the earlier figures and those of EMEP/CORINAIR (1995), while the values for Cd and Pb are lower. Table 1 allows certain conclusions and inferences to be drawn:

- Emission factors for certain metals, e.g. As, Ni, Pb, were significantly reduced between the 1980s and EMEP/CORINAIR (1995),
- EMEP/CORINAIR (1995) made clear distinctions between the types of emission, which could be expected from smelters processing Cu ore and those processing Ni-Cu ore, including differentiation of Ni:Cu ratios and of the type of trace metals which could be anticipated in each type of ore, e.g. higher Pb in Cu ores than in Ni-Cu ores.
- The latter development was not followed by Pacyna and Pacyna (2001), who, though they quote Boyd et al. (1998), who illustrate this problem, persist in the practice of applying the same emission factors to processing of all types of Cu, Ni-Cu and Ni ores.
- Pacyna and Pacyna (2001) introduce a geographic differentiation in their application of emission factors, a differentiation which must be based on the assumption that the metallurgical industries in Australia, North America and Europe have a level of efficiency

significantly greater than the corresponding industries in Asia, Africa and South America. This assumption is based on information reported from the three companies in North America and four in Germany, national reports from the USA, Canada and European countries, and on comparisons of smelters made in a source which the authors do not list in their reference list (Non/Ferrous Metal Works of the World), so that it is unclear which edition of this work has been used.

South Africa is the dominant producer of metals in Africa 45% (Europe and Globe, 2005), in general,, so that this categorization is based on an assumption of out-dated technology, which may not be relevant. The same applies to the mining and metallurgical industries in South America. On the other hand, Pacyna and Pacyna (2001) give an unjustifiably favourable categorization of European non/ferrous metal production (see next section).

4. Emission estimates at regional and continental levels

Table 2: Estimates of emissions (in tonnes) from smelting of copper and copper-nickel ores and of the total emissions from primary non-ferrous metal production in Europe.

Source	Sector and Geographic unit	Year	As	Cd	Cu	Mn	Ni	Pb	Sb	Sn	Se	V	Zn
NILU (1984), Pacyna (1995)	Cu-Ni Eur. Russia*	1978	616,0	85,0	1083	7,0	1120	1636	55,5		63,0		505
Murmansk CENR (1995)	Cu-Ni Kola Peninsula	1994			1097		1916						
Boyd et al. (1998, submitted)	Cu-Ni Kola Peninsula	1994	6,3	0,9				13	1,6			43,7	27
Pacyna et al. (1984), Pacyna (1986)	Cu-Ni Europe	1979	4490,0	595,0	7850			9250					2500
Pacyna (1987)	Cu-Ni Europe	1979	4500,0	600,0				9250					
Pacyna and Pacyna (2001)	Cu + Ni Europe	1995	185,0	92,0	555	2,0	277		19,0	19	19,0	9,0	370
Pacyna and Pacyna (2001)	Non-ferrous metals Eur.	1995	245,0	208,0	572	2,0	281	3341	62,0	19	48,0	9,0	3622
ESPREME (2006), Pacyna et al. (2007)	Non-ferrous metals Eur.	2000	132,0	52,0			49	1471					

The purpose of Table 2 is to facilitate comparison between published estimates of emissions from copper and copper/nickel smelters in Europe, and those from one of its most prominent contributors, the copper/nickel smelters on the Kola Peninsula in NW Russia, which are discussed in detail in Boyd et al. (1998, submitted), and information on emissions from smelters in other parts of Europe. The table clearly shows the results of the reduced emission factors described in relation to Table 1 above.

Comparison of the figures for the elements for which comparison between (Pacyna et al, 1984) and (Pacyna, 1986) on the one hand, and (Pacyna and Pacyna, 2001) on the other, is possible, shows:

- Reductions of over an order of magnitude in estimated emissions of As and Cu between 1979 and 1995,
- Reductions by a factor of c. 6.5 in emissions of Cd and Zn in the same period.

It is notable that Pb and Hg are included in the estimates of emissions of copper and copper-nickel smelters in the other continents (Pacyna and Pacyna, 2001), but not from those in

Europe. It is remarkable that the figure for Cu emissions in Europe as a whole in 1995 (Pacyna and Pacyna, 2001) is approximately half of the official figure for emissions of Cu from the smelters on the Kola Peninsula alone for the previous year (Murmansk CENR, 1995), a figure which has been confirmed by observational evidence (Chekushin et al., 1998; Boyd et al., 1998, submitted). The discrepancy is even greater for Ni, the figure in Pacyna and Pacyna (2001) being c. 15% of that in Murmansk CENR (1995), which is quoted by Pacyna in AMAP (2005). Pacyna and Pacyna (2001) state, in relation to the estimates in NILU (1984), "Only recently has this old emission inventory been updated and improved by studies carried out by ……. and Boyd et al. (1998)", but omit any comment on what the improvements represent and ignore it in their revised estimates. The figure for Cu, however, clearly does not take account of the smelting of copper ores of other types, which takes place on the European side of the southern Urals (Williamson et al, 2003, BRGM, 2003). Pacyna (2002) states "Heavy metals emitted from non/ferrous metal production decreased by a factor of two to three from the early 1980s to the mid-1990s. This is largely due to the improvement in emission control efficiency at major smelters in Europe and North America." While this is probably true for smelters in western and central Europe (Goonan, 2004), it is not true for Europe as a whole, given the level of emissions at smelters in Russia west of the Urals (Ekimov et al., 2001).

There is little doubt that significant reductions in emissions from smelters in many European countries were achieved in the period 1985-2000. KGHM, which operates four smelters in Poland (Europe's most important Cu producer after Russia), reports a dramatic reduction in emissions from 1985-2000 (http://www.kghm.pl), Cu emissions having been reduced from 315.6 t/a to 23.2 t and Pb emissions from 356.2 t/ to 13.8 t. By-products from the Cu production in Poland include Pb, Ni, Au, Ag, Pt, Pd and Se. There were, however, in 2002 a further 27 operating Cu smelters in Europe, in addition to those in Poland (Feliciano and González, 2002). These include the Bor smelter complex in Serbia (Peck and Zinke, 2006), which emits "high amounts" of Bi, Pb, Zn, Cu, Cd, Mn and Ti to the atmosphere and the Zlatna smelter in Romania, also recognized as a serious environmental threat (Pope et al., 2005): figures for actual emissions of metals from these smelters have not been found in readily accessible sources. The existence of Cu smelters using outmoded technology in Serbia and Romania argue for some doubt in relation to figures for total national emissions in these countries (respectively 31.2 and 25.8 t) in 2000 presented in a recent overview (Hettelingh and Sliggers, 2007).

ESPREME (2006) and Pacyna et al. (2007), based on the ESPREME database, give a new set of estimates of emissions from non-ferrous metal production in Europe for four of the metals included in Table 2 (and for Cr): these figures are based, with some upward adjustments, on reports from national authorities "to the UN ECE LRTAP Convention through the EMEP program" and their accuracy is indicated to be ±20%. Pacyna et al. (2007) include a figure showing the spatial distribution of arsenic emission in 2000, using grid cells of 50 x 50 km^2, on which none of the cells on the Kola Peninsula exceed a background level of 0.25 t/cell. While it is stated that these two sources are based on data sets submitted by national authorities, it is obvious from other sources, quoted by the same authors in other contexts (as indicated above), that there are serious weaknesses in parts of the data and that they can give a misleading impression to the unwitting reader, if taken out of context.

Table 3
Emissions from primary copper and nickel production at a continental level in 1995 (Table 3 in Pacyna and Pacyna, 2001) (note that the text in the paper states that the table shows "copper and nickel production", while the table text states "copper production") and reported emissions from Cu and Cu-Ni smelters in Canada for 1993 (Skeaff and Dubreuil, 1997).

Continent	As	Cd	Cu	Mn	Ni	Pb	Sb	Sn	Se	V	Zn
Europe	185,0	92,0	555,0	2,0	277,0	-	19,0	19,0	19,0	9,0	370,0
N. America	252	126	754	3	377	754	25	25	25	13	503
Canada	72	45	614	<1	497	652	<2	-	<3	-	249
Australia + Oceania	25	13	75		37	75	3	3	3	1	50
Asia	1593	637	9555	32	4778	3185	159	159	159	32	1593
Africa	260	104	1562	5	781	521	26	26	26	5	260
S. America	868	347	5207	17	2604	1736	87	87	87	17	868

The estimate given by Pacyna and Pacyna (2001) for North America can be compared with the reported emissions from Canadian Cu and Cu-Ni smelters (Skeaff and Dubreuil, 1997): the former authors stated that their estimates were "claimed to be more accurate" than those of the latter on the basis of the merits of the emission factors used. The comparison should recognize that the USA was a much more important producer of copper in 1995 than it is in 2008, with over double the mine and smelter production of Canada, but without significant nickel production (Mining Annual Review, 1996, 1997). The actual emission figures reported by Skeaff and Dubreuil (1997) show that 79% of the As, 60% of the Cu, 1% of the Ni and 80% of the Pb resulted from emissions from Cu smelters, as opposed to smelters which processed Cu-Ni ores (the data do not permit similar calculations for the other elements). This calculation points to the differences in chemistry between the Cu ores and the Cu-Ni ores being processed in Canada: it probably also indicates that the Pacyna and Pacyna (2001) figure for Cu emissions in N. America is too low, but it does not allow the same conclusion for the other elements because of the difference in the type of Cu deposit which dominates production in the USA.

Australia's production of Cu and Ni in 1995 was respectively 473,000 and 102,600 Mt respectively, but it is not possible to make a direct comparison with production figures and emissions for Canada or North America because 73% of Australia's production of Cu ore, at least in 2002 (Goonan, 2004), was exported for smelting in Japan (65%), Korea (4%) and China (4%).

The major producers of copper in Africa are Zambia, S. Africa and DR Congo, with 4.2% of world production in 2005: Ni production, mainly from Botswana and S. Africa, was c. 4.9% of world production (BGS, 2007). Cu production in Zambia and the Congo (lower in 1995) was entirely from sedimentary copper deposits, while the sole producer in S. Africa was the Palabora carbonatite-hosted deposit (Table 4): these types of mineralization do not contains major trace contents of Ni or Pb: the 2:1 ratio for Cu:Ni and the 3:2 ratio for Ni:Pb applied by

Pacyna and Pacyna (2001) for Africa and S. America (see Table 3) thus lead to emission estimates which are incompatible with the composition of the ores being exploited in Sub-Saharan Africa.

Table 4: Main types of Ni and Cu ores, their most common trace metals (minor ones in brackets) and major producing countries, the most important ones in bold font. (Sources: Mining Annual Review 2003, BGS (2007), Golightly (1981), Gustafson and Williams (1981), Herrington et al. (2005), MINEO (2003?), Naldrett (1981)

	Ore Types	Common Trace Metals	Europe	N. America	Australia + Oceania	Asia	Africa	S. America
Ni	Ni-Cu (± PGE) sulphides	As, Cd, Co, Hg, Pb, Se, Te, Zn (Sb, PGE)	**Russia**, Spain	**Canada**	**Australia**	**Russia**, China	S. Africa, Botswana, Zimbabwe	
	Ni-Co laterites	Cr, Mn, Cu, Ti, Sc	Greece, Russia		**New Caledonia**, Australia	**Indonesia**, Philippines		Cuba, Brazil, Dominican Rep., Colombia, Venezuela
Cu	Sedimentary Cu	Ag, As, Co, Cr, Ni, Pb, Se, Zn (Cd, Mo, PGE, U)	**Poland**			**Russia**	**Zambia**, Congo	
	Volcanogenic Cu-Zn(-Co)	As, Cd, Hg, Pb, Sn	Russia	Canada	Australia	Kazakhstan*		
	Porphyry Cu(±Mo±Au)	As, Cd, Cr, Pb, Sb, Se, V, W, Zn	Bulgaria, Sweden	USA, Mexico		**Indonesia**, Iran, Mongolia, Uzbekistan		**Chile**, Peru, Argentina
	Fe-Cu-Au(±U)	As, Ba, Co, P, F, Mo, Ni, REE			**Australia**, Papua New Guinea			Chile, Brazil
	Carbonatite Cu(-U)						S. Africa	
	Epigenetic Cu(-Au)							
	Skarn Cu							

A similar situation, though with a different geological explanation, applies in S. America: Chile and Peru supplied over 40% of global Cu production in 2005, mainly from porphyry Cu deposits in which trace levels of Ni are negligible (Table 4). This type of deposit does not contain Ni as a significant trace element, neither in the ore nor in the host rocks which host the ore, and the linkage between emissions of Ni and of Cu indicated in Table 3 (Pacyna and Pacyna, 2001) is incorrect. Arsenic is, however, an important trace constituent in deposits of this type. CODELCO, the national Chilean Cu producer, operates three of the seven Cu smelters, which operate in Chile (Feliciano and González, 2003): CODELCO reported emissions of As of 3,120 tons in 2000 and 960 tons in 2003. The CODELCO smelters represented, in 2003, just under half the smelter capacity for Cu in S. America (there are another four smelters in Chile, two in Peru and one in Brazil) (Feliciano and González, 2003): viewed in this context, there is reason to believe that the estimate of 868 t of As emitted from Cu and Cu-Ni production in S. America in 1995 (Pacyna and Pacyna, 2001) is much too low, probably by an order of magnitude (CODELCO's web page does not give data prior to 1999, but the figure for As emissions in CODELCO's three smelters in 1999 is 5,340 t.).

Nickel is produced in S. America, from operations in Brazil, Columbia and Venezuela, and there is a Ni smelter in Brazil, the only one in S. America (BGS, 2007). This smelter, at Pratapolis, processes low-grade Ni-Co laterite, the predominant Ni resource exploited to date in S. America, which does not contain the same trace element spectrum as the Ni-Cu sulphide ores which are the world's most important source of Ni. This is a further argument against the use of standard emission factors for estimation of emissions from continent to continent.
The range of deposit types, the number of smelters (nineteen Cu smelters in China alone (Feliciano and González, 2003)) and the difficulty in finding relevant information pose problems in making general comments on the figures for Asia given in Table 3. It can, however be noted that official figures are available for emissions of Ni and Cu from Noril'sk: these are 1,280 t Ni and 2,380 t Cu for 1994 (Surnin et al., 1997). These are as would be expected from a Ni-Cu sulphide deposit in which the Cu content exceeds that of Ni. China's smelter production (Jinchuan smelter) of Ni in 2005 (BGS, 2007), from a broadly similar type of ore, was c. 33% of Russia's. China has, however, almost 20% of the world's smelter capacity for Cu (BGS, 2007), and could be expected to have significant emissions from these Cu smelters.
It could be said that the above analysis should be more comprehensive: the limitations include:

- The lack of publicly available data of any kind on emissions from or impacts of many of the smelter complexes.
- The existence of data in forms which are not easily accessible, either because of language or type of source.
- The lack of more detailed knowledge on the chemistry of the raw materials being processed. General knowledge of ore types and ore chemistry can indicate the spectrum of trace metals which can be anticipated in emissions from a smelter which processes ore from well-documented deposits, but this information is readily available in only a few cases.

The analysis does, however, document that quite basic knowledge on the nature and chemistry of a range of ore types can be used to document serious weaknesses, including errors of an order of magnitude in both directions (too high and too low), in published estimates of emissions from the non-ferrous metal industry, which have appeared over a period of over twenty years, most recently in Pacyna and Pacyna (2001) and Pacyna et al. (2007) and which have been employed in a range of applications at scientific and political levels. This conclusion is based on a consideration of only one sector within this industry.

5. Broader perspectives

5.1. Regional impact of emissions from smelting of Cu and Ni-Cu ores

Most of the papers cited in the introduction to this paper consider smelter emissions in a national, continental or even global context. Several of the papers, e.g. Pacyna et al. (1984)

and Akeredolu et al. (1994) postulate long-range atmospheric transport of a range of trace metals from sources in industrial centres in northern Europe and Asia to the Arctic. However, Dietz et al. in AMAP (1998) state that "models of long-range transport, deposition and modification of heavy metals in the Arctic are incomplete at the present" and Barrie et al. (1992), in an assessment of the conclusions of Akeredolu et al. (1994), then "in press", stated: "Apparently a large fraction of pollutants entering the Arctic are not deposited there but rather are carried on the winds back out of the region". Marcy, in AMAP (2005), stated that "Compared to global background levels …atmospheric concentrations of heavy metals in the Arctic were low except near point sources." was one of the conclusions from the first AMAP assessment, a conclusion which is supported and amplified in the conclusions of AMAP (2005). While AMAP (1998) covered a broad range of heavy metals, focus in AMAP (2005) is on Hg, Pb and Cd, a priority based on their toxicity, the fact that Hg is easily transported in a gaseous form and that Pb, because of its use as an additive in fuel, occurs at very fine particle sizes.

In parallel with, and after production of AMAP (1998), several comprehensive studies on regional and local scales have provided solid documentation of the fact that the bulk of the heavy metals emitted from smelter complexes on the Kola Peninsula are deposited within 50 km of the source, and that they, even with modern analytical methods, are not discernible relative to background levels beyond 100-200km from the source (Reimann et al., 1997, 1998). This is supported by the results of geochemical mapping of the Eastern Barents Region (Salminen et al., 2004) and by the detailed studies around Cu smelters in Canada (Zdanowicz et al., 2006; Bonham-Carter et al., 2006; Goodarzi et al., 2006). As for the metals prioritised in AMAP (2005), Reimann et al. (1998) show that these metals are not discernible relative to background levels in moss beyond 100 km from the smelters on the Kola Peninsula. There is thus a considerable literature which documents that Cu and Cu-Ni smelters, while they may, without modern technology for emission abatement, have a dramatic impact on the environment and health of living organisms in their vicinity, are point sources, depositions from which are not detectable in relation to other contributing features beyond 200 km and whose negative impact is felt within a more limited range. It is probable that this also applies to most of the other sectors of metal production covered by Pacyna and Pacyna (2001). It is important to have better knowledge of the emissions from these sources, and of their consequences but they are statistical "outliers" in relation to regional-scale emissions caused by several other anthropogenic (many of them linked to population distribution) or to many geogenic sources, and contribute to a misleading impression when aggregated with estimates from these sources.

5.2. Another type of anthropogenic source

The phrase "anthropogenic source" appears in the titles of several of the papers cited, e.g. Pacyna (1986b), Pacyna and Pacyna (2001) and Pacyna et al. (2007). Pacyna (1986b) considers forest fires as a major emission source in certain parts of the world, but includes these as a natural source. It is, of course, the case that forest fires can, in many parts of the world be caused by lightning, but there is good evidence (http://asdwww.larc.nasa.gov/biomass-burn/globe_impact.html) that by far the greatest proportion of forest fires is man-made, either in connection with traditional forms of agriculture, as in many areas of savannah in Africa, or as a means of clearance of natural forest, aimed at new cultivation. The peak periods for burning of vegetation are, inevitably, in the dry seasons, when there is no lightning which can cause natural fires. Van der Werf et al. (2006) have employed satellite data and biogeochemical modelling to calculate emissions of total carbon and a range of gases from global biomass burning: for sub-Saharan Africa alone, in 2000, emissions of C were calculated to be 1,232 million tons, approximately 60% of the global total. The level of trace-metal emissions from this source is a function of the varying geological environment and the biogeochemical properties of the plant species being consumed, which would also vary. Breulmann et al. (2002) showed that the leaves of tropical trees in Sarawak, Malaysia, contained > 8 ppm Cu and Ni, attributing an increase in the previous four years to increased metal accessibility following long-term forest fires. Gaudichet et al. (1995), using data from test firing of savanna in the Ivory Coast, showed that, i.a. Cu and Zn were significant products from burning of the vegetation, not the soil: they estimated that the annual flux of Zn from combustion of African savannah was 8,000 t/a, equivalent to 14% of the estimate given by (Pacyna and Pacyna, 2001) for worldwide emissions of Zn from major anthropogenic sources in the mid 1990s. Yamasoe et al (2000) have estimated the following annual emission fluxes of metals from annual burning of savannah and tropical forest: 1,600 ± 900 t Mn, 3,200 ± 1,700 t Zn and 1,140 ± 430 t Cu. These figures, even taking account of the large margins of error are a significant contribution to anthropogenic emissions of these metals.

6. Conclusions

Emission factors have been applied to estimate emissions from smelting of Cu and Cu-Ni ores in situations where direct observational data is not available. Basic knowledge on the chemistry and mineralogy of the raw materials being processed has been neglected: this has led to the establishment of emission estimates, which, though adjusted over time, still, in their most recent forms (Pacyna and Pacyna, 2001) have errors at the level of orders of magnitude for certain metals, in some cases too high and in other cases, too low. Similar assessments should be made of the emission estimates presented in the above-cited sources for production of lead, zinc and iron/steel. Reliable estimates will not be achieved without systematic input from the metallurgical industry, and from geoscientists who have knowledge of the raw materials being processed. These sources of emissions can, in the absence of appropriate abatement technology, cause serious damage to their immediate environment, immediate being a radius of 50-200 km. They are not, however, unlike certain source categories which are related to population density or biomass burning, impact factors on a continental scale.

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