PROCEEDINGS OF THE INAUGURAL WORKSHOP
IGCP/SIDA No. 594, KITWE/ZAMBIA, OCTOBER 17TH–18TH, 2011

MINING AND THE ENVIRONMENT IN AFRICA

Edited by Bohdan Kříbek

CZECH GEOLOGICAL SURVEY, PRAGUE 2011

MINING AND THE ENVIRONMENT IN AFRICA

CZECH GEOLOGICAL SURVEY, PRAGUE 2011

PRESENTED IN ASSOCATION WITH

FIELD TRIP ORGANIZED IN COOPERATION WITH

COVER PHOTOGRAPH

Reprocessing of old slag in the Chambeshi Smelter

COVER DESIGN

Štěpán Bartošek

The authors are fully responsible for scientific content, language and copyright of submitted figures and data of their articles.
The manuscript has not passed through the editorial work
of the Publishing Department of the Czech Geological Survey, Prague.

The texts of the various papers in this volume were set individualy by typists under the supervision of each of the authors concerned.

PROCEEDINGS

MINING AND THE ENVIRONMENT IN AFRICA
Editor: Bohdan Kříbek
Published by the Czech Geological Survey
Klárov 3, 118 21 Prague 1, Czech Republic
Technical editors: Vladimír Majer, Jan Kříbek
Printed in the Czech Geological Survey, Klárov 3,
Prague 1, Czech Republic

ISBN 978-80-7075-119-0

PROCEEDINGS OF THE INAUGUAL WORKSHOP
IGCP/SIDA No. 594, KITWE/ZAMBIA, OCTOBER
17th-18th, 2011

MINING AND THE ENVIRONMENT IN AFRICA

Edited by Bohdan Kříbek

PREFACE AND EDITORIAL COMMENTS

A large amount of information regarding the contamination of mining sites in different parts of the world has been collected by carrying out systematic geochemical sampling, analysis and interpretation of obtained data. This has led to better understanding of the cause and effect that created an impetus for a new environmental legislation and strategies for remediation of polluted regions in many developed countries. In Africa, because of economic pressures and slower evolution of environmental awareness, local communities have particularly been exposed to the detrimental effects of mining contamination on public health, agriculture and the environment. During the last twenty years environmental experts and organizations from South Africa, Europe, Australia and North America have increasingly cooperated with their counterparts in other African countries in a number of projects implemented in various countries of this continent. However, these geochemical investigations tended to be focused on the effects of mining and mineral processing at national level and in specific mining districts without taking into account the overall impact on larger hydrological and environmental domains across the continent. In environmental issues, the cross-border cooperation and liaison between the African governments and institutions have so far been limited. Consequently, there is sufficient scope for sharing the knowledge of monitoring methods and for developing a common approach to the management and interpretation of geochemical data so that natural anomalies can be assessed and distinguished from those caused by mining and related industrial activities, taking into account the geology, topography, climate, vegetation and hydrology in different regions of Africa.

Therefore, a new IGCP project No. 594 entitled ASSESSMENT OF THE IMPACT OF MINING AND MINERAL PROCESSING ON THE ENVIRONMENT AND HUMAN HEALTH IN AFRICA was proposed to the International Geological Correlation Programme (IGCP) Board in 1010, and approved by the Board in 2011.

The project is designed (1) to correlate and integrate the results of multidisciplinary studies carried out in contaminated sites and areas using the best contemporary procedures for statistical analysis, management and compilation of the geochemical data; (2) to strengthen the capacity of African institutions in environmental geochemistry by cooperation with foreign experts and organizations, (3) to raise public awareness of the impacts of mining on the environment and human health and, (4) to facilitate cooperation among geoscientists and medical scientists.

The Inaugural Workshop of the Project is scheduled to take place at Kitwe, Zambia, from October 17th to 18th, 2011.

Extended abstracts given in this volume are to be presented in oral form or as posters during the above-mentioned Inaugural Workshop

On behalf of the Organizing Committee of Inaugural Workshop we wish to thank all institutions which participated in preparation and organization of this meeting. Special thanks are due to Mopani Copper Mines Plc for support and cooperation in the organization of post-workshop field trip to the Copperbelt Area.

Our thanks are also directed to all experts who will participate at Inaugural Workshop and who intend to present their papers of which extended abstracts are given in this Volume. It is a very pleasant duty to thank all reviewers for their valuable comments on submitted papers.

Special thanks are due to Vladimír Majer and Štěpán Bartošek for having revised the English and proofreading of abstracts text.

The Volume would not have been published without a great effort of the Editorial and Publishing Department of the Czech Geological Survey.

In conclusion, it is a great pleasure of the Organizing Committee to wish all participants in the Inaugural Workshop a pleasant stay at Kitwe.

Prague, October 5, 2011

Bohdan Kribek et al

ORGANIZING COMMITTEE

CHAIRMAN

Bohdan Kříbek, Czech Geological Survey, Prague

CO-CHAIRMEN

Peter Sinkamba, Citizens for the Better Environment, Kitwe
Kenneth Maseka, University of the Copperbelt, Kitwe
Imasiku Nyambe, University of Zambia, Lusaka
Benjamin Mapani, University of Namibia, Windhoek
Gloria Kayula, Citizens for the Better Environment, Secretary
Růžena Čadská, Czech Geological Survey, Tresurer

TABLE OF CONTENTS

The borax method – a safe way of extracting gold for small-scale miners

Peter W. U. Appel
Geological Survey of Denmark and Greenland
pa@geus.dk

Leoncio Na-Oy
Benguet Federation of Small-scale miners,
naoyleoncio@yahoo.com

Emy Perez
imeldificperez@yahoo.com

Abstract. Borax gold extraction has been carried out in the Philippines for over thirty years and presently around 15000 small-scale miners (ssm) use the method. Early 2010 the method was successfully tested in the Mbeya region of Southern Tanzania. In Ghana a recently completed EU funded project proved that the borax process worked on Ghanaian gold ores. A very successful teaching and training programme of the use of borax in gold extraction was carried out in August 2011 in the Philippines. Borax reduces melting point of minerals including gold to such an extent that small-scale miners can melt gold out of their concentrates in their villages without using sophisticated equipment. All what is needed is borax, a clay bowl, a hand-powered blower and a charcoal burner of the type used for cooking. The borax method of in situ melting of gold provides an environmentally benign gold extraction method. Borax is not only environmentally benign but it is shown to increase gold recovery considerably. The borax method also produces high quality of gold with no traces of mercury which will fetch a higher price than gold produced by amalgamation.

Keywords. Small-scale gold mining, mercury, borax

1 Background

The Philippines is heading for a major environmental and health disaster caused by release of 200 to 500 tons of mercury every year. The Minamata mercury disaster which is the worst mercury caused disaster in the history of mankind caused death of thousands of people and many more children were born mentally and physically crippled. It is thus obvious that the Philippines will experience a disaster several orders of magnitude worse than the Minamata disaster.

The mercury stems from small-scale gold mining, where 200 000 to 400 000 small-scale miners use mercury for extracting gold every day. The total production of gold by small-scale miners exceeds the amount extracted by commercial mining companies. These miners thus contribute significantly to the GNP of the Philippines.

The miners use gold extraction techniques which are not efficient and which cause major release of mercury to the environment and major loss of gold for the miners. The miners do not realise that they lose so much gold.

However, there is a solution to this problem next door. In the Benguet area a group of small-scale miners have adopted a non-toxic gold extraction technique called the borax technique. This is used daily in that part of the Philippines and should be promoted to other part of the country. Recently a small-scale miner from Benguet was brought to Tanzania to teach small-scale miners there to use the borax method.

In order to avoid the impending environmental disaster two avenues must be followed.

1. Cleaning all the tailings from the miners for mercury
2. Teaching the small-scale miners a non toxic gold extraction technique.

2 Possible ways out of the impending mercury disaster

2.1 Mercury gold extraction

The vast majority of small-scale gold miners use mercury to extract the yellow metal. The amount of mercury used to extract gold varies considerably. In Tanzania the ratio is in the order of 1 gram of mercury extract 1 gram of gold whereas the ratio in the Philippines is 30 to 50 gram of mercury to extract one gram of gold.

The environmental and health problems are immense and numerous methods have been tested in order to reduce release of mercury from small-scale gold mining. Most of those methods were either too costly or too technological for the miners; they maybe took too long time or were not efficient.

2.2 Borax method

About thirty years ago a bunch of small-scale miners in Northern Philippines realised that the chemical borax, which was normally used for cleaning purposes had the ability to reduce the melting point of minerals including gold. They tried whether it worked on the gold concentrates and found the melting point of gold was reduced so much so a miner could melt gold out of his concentrate in his village without using more than a clay bowl, a charcoal burner (normally used for cooking food) and a and a simple blower.

The method is now gradually spreading. The Geological Survey of Denmark and Greenland together with a miner from the Philippines held successful training sessions in two mining communities in Tanzania.

The method is described in detailed at the poster displayed at the Inaugural meeting in Kitwe October 2011.

2.3 Recent success story

In August 2011 a small-scale miner in the Philippines taught a group of other small-scale miners who were using mercury. The training took place over a week and the miners discovered that their recovery of gold almost rose 100%.

Sources of exposure to cobalt and other metals in populations from Likasi and Lake Changalele in Katanga, D.R. Congo

C.L.N. Banza, J. Asosa, L. N. Kabamba & A. Mutombo
Unité de Toxicologie et Environnement, Ecole de Santé Publique, Université de Lubumbashi, Lubumbashi, D.R. Congo
celestinlubabankulu@yahoo

V. Haufroid
Laboratoire de Toxicologie Industrielle et Médecine du Travail, U.C. Louvain, Brussels, Belgium

Th. De Putter
Geology, Royal Museum for Central Africa, Tervuren, Belgium

B. Nemery
Occupational, Environmental and Insurance Medicine, Department of Public Health, K.U.Leuven, Leuven, Belgium

Keywords. Cobalt, dust, water, fish

1 Introduction

In a biomonitoring study (Banza et al. Environ Res 2009) of over 350 subjects we reported that the population of Southern Katanga is substantially exposed to several metals or metalloids, with subjects living within 3 km of mines or metal smelters having significantly higher urinary concentrations of As, Cd, Co, Cu, Pb and U, than those living farther away. In this follow-up study we evaluated the exposure of subjects living in two areas (Shituru & Panda) of Likasi, a town with copper/cobalt processing plants, three villages (Shinangwa, Kibangu, Kansalabwe) close to Lake Changalele, which receives water that is contaminated by the Likasi industry, and two control villages (Kidimudilo, Misisi-Sando).

2 Methods

In the various locations, we obtained urine samples from male and female adults and children (n=23 to 42), as well as samples of drinking water, outdoor and indoor dust, locally grown vegetables, locally caught fish, and chickens. The concentrations of metals (and metalloids) in these samples were analyzed by ICP-MS.

3 Results

The urinary metal concentrations were generally significantly and substantially higher in Likasi, than in the villages close to Lake Changalele and the control villages (e.g. median Co: 21.3, 10.5 and 4.6 µg/L, respectively). Similarly, the concentrations of metals in indoor dust were considerably higher in Likasi, than in the other locations (e.g. median Co: 372, 9 and 30 µg/g dust, respectively). This was also the case for Co in liver and kidney of chickens. Median Co-concentrations were 10-fold higher in Tilapia fish from Lake Changalele (2.8 µg/g dry flesh) than from other locations in the Lualaba river (0.25 µg/g dry flesh). Although surface waters were considerably polluted, the metal concentrations in drinking water (distribution or wells) were below WHO guidelines

4 Discussion

These preliminary analyses confirm that subjects living close to the sources of industrial pollution in Katanga have high concentrations of metals in their urine. The main source of the contamination appears to be the presence of metals in dust. However, the consumption of fish may also contribute to the uptake of some metals (especially Co) in the populations living close to the Lake who, presumably, consume high amounts of contaminated fish. Further detailed determinations are needed to apportion the various potential sources of intake.

Overview of the hydrochemistry and water quality in areas influenced by gold mining activities in West and South Birrimian of Mali

H. Bokar, A. Mariko, A. Z. Tratore, F. Bamba
Ecole Nationale d'Ingénieurs Abderhamane Baba Touré (ENI-ABT), DER Géologie, Unité Eau/Environnement, BP 242, Bamako ,Mali, hamadounbokar@yahoo.com

L. Seguis
IRD Montpellier France

A. N. Tratore
Direction Nationale de la Géologie et des Mines, Mali

M. Fofana
Laboratoire nationale des Eaux, Mali

Abstract. The present study is based on the influence of gold mining activities on the quality and hydrochemistry of regional surface water and groundwater within the Birrimian areas of Mali. The study areas are located in the sub-catchments basins of Bani and Sankarani in Niger River basin and Faleme in Senegal River basin. Data of 623 surface water and groundwater samples collected in the west and south Birrimian of Mali from 2002 to 2010 were used. Among these more than 200 samples were collected in gold mine sites as well as some artisanal gold extraction sites. The chemical species analysed were major anions and cations as well as, Cu, Fe, Mn.

Statistical analysis of all chemical species was done and concentrations were compared with World Health Organization (WHO) limits for drinking water since Malian standards are not yet available. The results showed that the concentrations of most of these elements were below the WHO limits. However, Cu, Mn, Fe, TDS and SO_4^{2-} concentrations are higher than the limits in many samples especially in those located in the environment of gold mining industries. Highest concentration values generally occurred in shallow wells.

Keywords. Hydrochemistry, water quality, gold mining areas, Mali

1 Introduction

Gold extraction became a major economic activity in Mali since 1990, and is now the second source of foreign exchange for the government after cotton. This rapid growth has raised many hopes in the development of the country since the gold price is still rising on the world markets. In 2003, with 54.5 tons extracted, Mali became the third largest gold producer in Africa behind Ghana and South Africa. This rapid economic growth has also created negative impacts on the environment such as water pollution. The study areas are located in the area of Birrimian of Mali. These Birrimian formations are present in Mali, Burkina Faso, Senegal, Ghana, Ivory Coast, Niger and Guinea Conakry. Hundreds of companies are exploiting the Birrimian south and west of Mali, among them are Sadiola Mine, Loulo Mine, Tabakoto Mine, Wassoulou Or Mine, Morila Mine, Kalana Mine, and Syama Mine and many artisanal gold extraction sites (Kola, Fatou, Kalaka, Massioko and many others).

Mining produces pollution and its impacts on environment and human health are yet to be well understood in developing countries. Some authors have documented some of the issues that arise as a result of environmental pollution (Nriagu, 1989; Förstner et Wittmann, 1981; Salomons et Förstner, 1984). In West Africa main studies have been done on impacts of heavy metals and most of these studies have been concentrated in Nigeria and Ghana (Mombeshora et al. 1983; Ntow et Khwaja 1989; Donkor et al. 2006). In Mali studies are limited to global socio-environmental aspect (Keita 1996, 1998, 1999) and none of the studies was focused on the impact of mining pollution on water resources.

The the geology associated with gold mineralisation extends from the Precambrian basement which covers nearly 160,000 km² in the south and west of Bamako and to the south in Ivory Coast and Guinea and west in Senegal. The regional geological investigations showed that the formations of Birrimian south appear as bands of a few tens of kilometres of width and extend for several hundreds of kilometres south and west of Bamako. They are separated by granitized or migmatized zones (Bassot et al. 1986; Feybesse et al. 2000). These crystalline rocks correspond, either to a pre-Birrimian basement, or a late granitisation related to the orogenesis, tectonic and metamorphic Birrimian formations. The early Birrimian is constituted with dominant detrital and volcano-detrital formations, while the late Birrimian with volcanic sediments. The crystalline rocks are represented by granitoids.

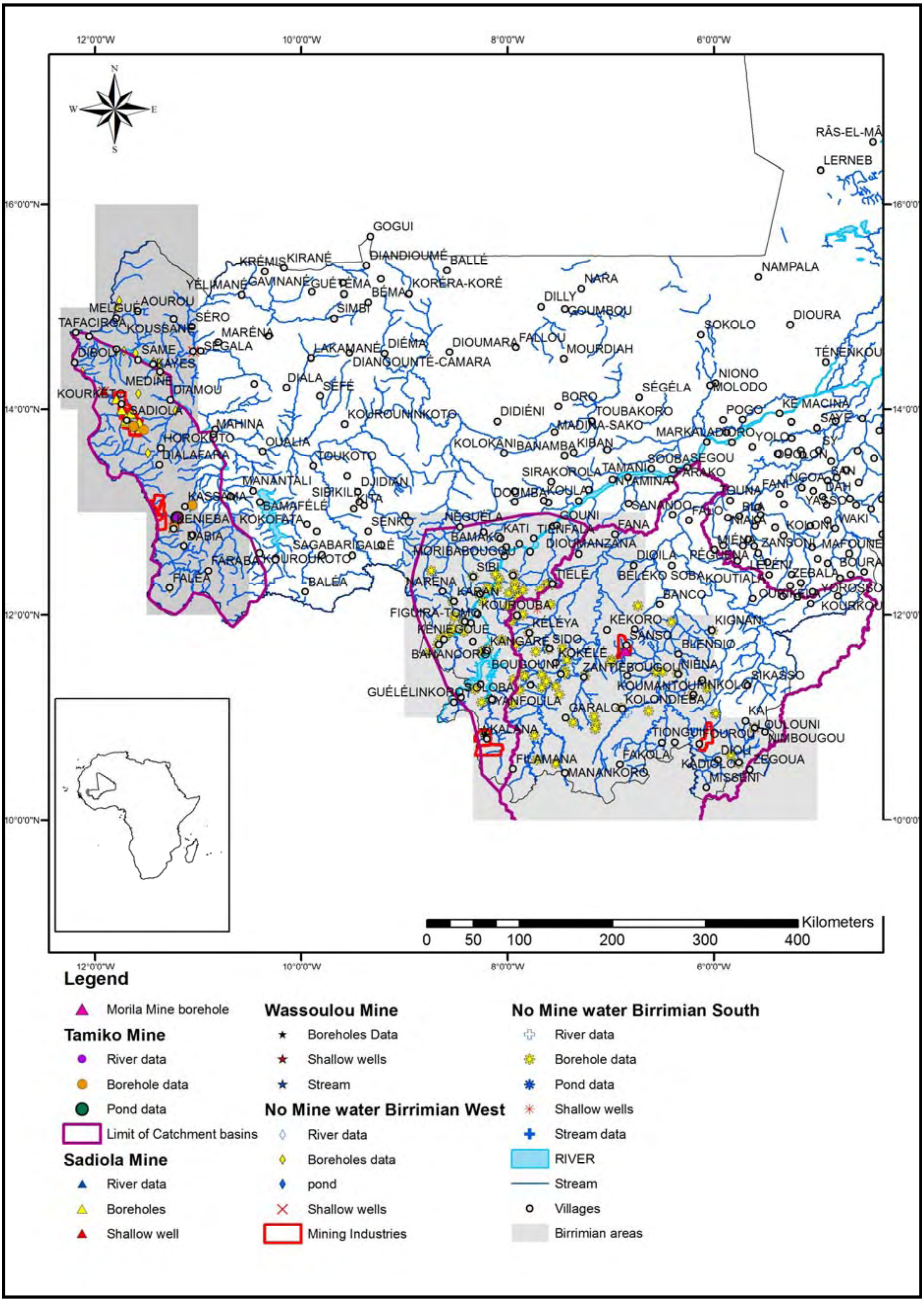

Figure 1. Location of water sampling area.

The lateritic and alluvium formations are present in the area and cover the crystalline basement. Some boreholes drilled in the area showed that the thicknesses generally exceeding 20 m above the granitic substratum and often higher than 50 m on the Birrimian formations.

Hydrogeological conditions are directly related to the geological and tectonic structure of the area. Therefore two aquifers compose the hydrogeology of the area: a fractured aquifer and a fissured basement.

The study area is divided into three catchment basins (Figure 1). One is the sub-catchment of the Faleme in the Birrimian west and the other two are sub-catchments of Sankarani and Bani in the Birrimian south.

2 Data and Methods

Data used for the study were collected from 2002 to 2010 and analyzed for chemical species at the national laboratory of water of Mali. The chemical species were major anions and cations as well as, Cu, Fe, Mn.

In order to determine water chemical facies, Piper diagrams were used. Statistical studies was also done in order to detect relationships between chemical species and origin of the water.

3 Results and Discussions

The chemical characteristics of water facies on the basis of major ions concentrations were determined by Piper diagram (Figure 2). Accordingly, the dominant type of water in the region is considered to be Ca-Mg-HCO_3 (magnesium or calcium-bicarbonate type). Moreover, the Ca-SO_4^{2-} (calcium sulfate type), groundwater type is also present in some surface and groundwater samples especially in shallow wells around gold mines. This later groundwater type could be originating from ore sulfide oxidation in the mining environment. Few samples constitute Ca-Mg-Cl type.

Table 1. Statistic of chemical species in water samples located in Birrimian - West

Chemical Species (mg/L)	*Ca*	*Mg*	*Na*	*K*	*TFe*	*Mn*	*Cl*	*SO4*	*CO3*	*HCO3*	*NO3*	*Cu*
Mean	23.91	32.51	39.27	5.52	0.24	0.00	27.38	48.73	1.37	205.78	3.97	0.04
Median	16.83	23.78	16.30	3.00	0.07	0.00	6.00	5.75	0.00	200.00	1.40	0.00
Stand. Dev.	29.62	36.69	81.08	10.73	0.46	0.02	84.35	138.67	18.92	125.16	8.68	0.43
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	335.80	358.17	940.00	168.00	**3.28**^{1}	0.30	**1150**^{2}	**1525**^{3}	392.40	688.00	90.50	**7.22**^{4}
N	443	443	443	443	443	443	443	443	443	443	443	443

1 – Shallow well Sadiola Mine 2- Shallow well Sadiola Mine 3- Shallow well Sadiola mine 4 – borehole TAMICO Mine

Table2. Statistic of Chemical species in water samples located in Birrimian - South

Chemical Species (mg/L)	*Ca*	*Mg*	*Na*	*K*	*Tfe*	*Mn*	*Cl*	*SO4*	*CO3*	*HCO3*	*NO3*	*Cu*
Mean	13.87	10.45	21.75	5.59	0.21	0.01	6.80	25.57	0.82	96.60	2.19	0.01
Median	8.46	6.61	11.00	3.35	0.03	0.00	3.23	1.63	0.00	79.50	0.80	0.00
Stand.Dev.	24.95	13.56	66.62	10.57	0.47	0.04	18.93	128.35	9.16	90.77	5.51	0.09
Minimum	0.80	0.59	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	304.60	106.70	808.00	118.00	**3.77**^{1}	0.50	**210**^{2}	**1350**^{3}	120.00	660.00	48.00	**1.14**^{4}
N	180	180	180	180	180	180	180	180	180	180	180	180

1-Borehole Kangaba, 2-Shallow wells Kola artisanal Mine 3- Shallow well Kola artisanal Mine 4-Borehole at Faboula artisanal mine

Statistical analysis showed a correlation between Ca^{2+} ions with almost all major ions this indicated that Ca remains the main major cations. The correlation is strong between Mg^{2+} and HCO_3^- that would suppose a more significant water/rock interaction with Mg minerals. Na and Ca weak correlation may be explained by cation exchange occurring in some samples. The correlations of NO_3^- with SO_4^{2-}, NO_3^- and Cl^- showed that these species may originate from anthropogenic activities.

Based on the analyzed data, most of groundwater from boreholes could be recommended for drinking while shallow wells and surface water were vulnerable to pollution especially those located in gold mining environment. More than 80% of analyzed samples can be used for agricultures as their sodium absorption rates (SAR) were low.

Acknowledgements

We thank FSP-RIPIECSA project for the financial support.

References

Bassot, J.P., Dommanget, A.. (1986): Tectonique : Mise en évidence d'un accident majeur affectant le Protérozoïque inférieur des confins sénégalo-maliens. Compte rendu de l'Académie des sciences de Paris.17, tome 302, pp 1101-1106.

Förstner, U., Wittmann, G.T.W. (1981): Metal pollution in the aquatic environment. 2nd edition. Berlin, Springer, 486 p.

Kouamelan, A.N. (1996): Géochronologie et géochimie des formations archéennes et protérozoïques de la dorsale de Man en Côte d'Ivoire. Implications pour la transition Archéen– Protérozoïque. Mémoire Géosciences Rennes, 73p.

Keita, S. (1996) : Le développement de l’industrie minière au Mali et études d’impact sur l’environnement. Bamako : PDRM.

Keita, S. (1998) : Un exemple de gestion intégrée de l’environnement minier-cas de la mine d’or de Sadiola-Mali : Cours sous-régional sur les paramètres géologiques pour la protection de l’environnement Bamako, du 9 au 19 décembre 1998.

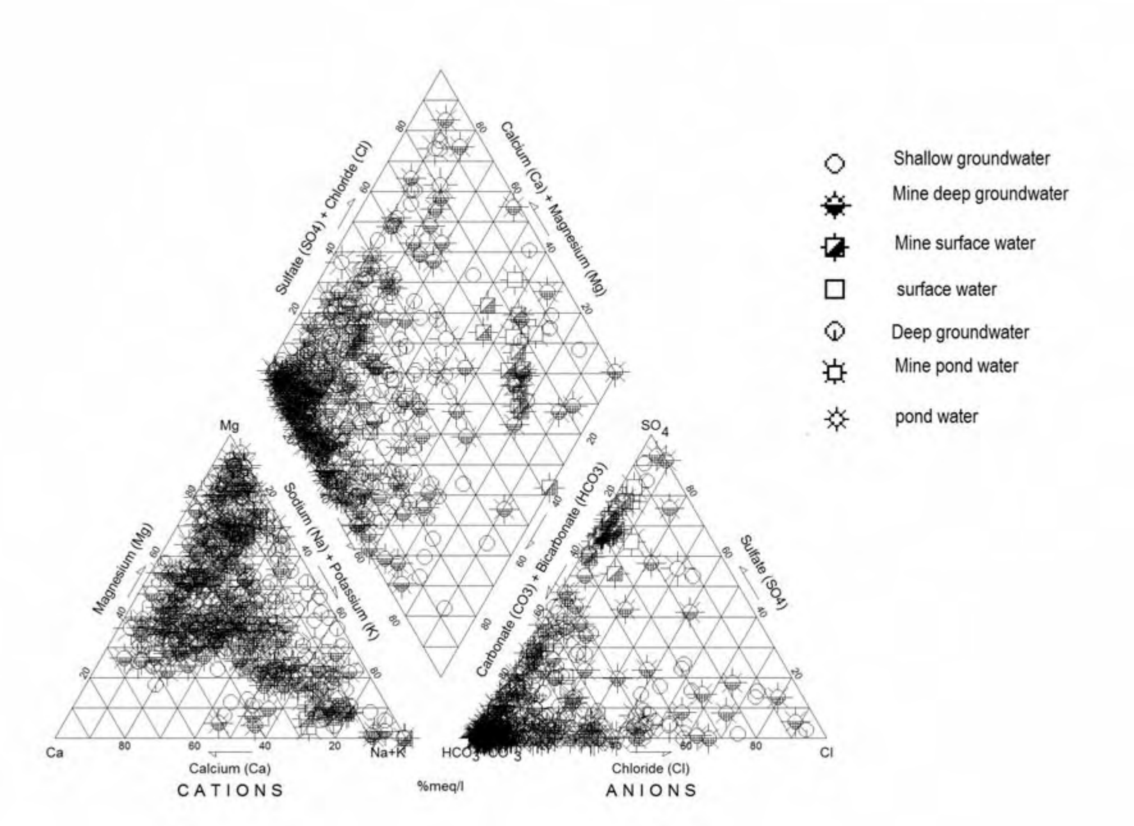

Figure 2. Piper diagram showing the groundwater chemical type in the Birrimian area.

Table 3. Correlation coefficient among water quality parameters.

	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	TFe	Mn^{2+}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	HCO_3^{-}	NO_3^{-}	TDS
Ca^{2+}	1.00											
Mg^{2+}	**0.54**	1.00										
Na^{+}	**0.20**	**0.13**	1.00									
K^{+}	**0.19**	0.10	**0.38**	1.00								
TFe	-0.09	-0.15	-0.05	0.02	1.00							
Mn^{2+}	-0.04	-0.05	0.05	-0.03	**0.30**	1.00						
Cl^{-}	**0.27**	**0.56**	**0.10**	0.10	-0.06	-0.01	1.00					
SO_4^{2-}	**0.57**	**0.33**	**0.64**	**0.34**	-0.05	-0.01	**0.17**	1.00				
CO_3^{2-}	0.01	0.01	**0.43**	**0.45**	-0.02	-0.01	0.06	**0.36**	1.00			
HCO_3^{-}	**0.30**	**0.62**	0.14	0.04	-0.23	-0.10	**0.15**	0.11	0.10	1.00		
NO_3^{-}	**0.52**	**0.44**	**0.19**	**0.25**	-0.01	-0.01	**0.22**	**0.19**	0.00	0.12	1.00	
TDS	**0.61**	**0.78**	**0.50**	**0.29**	-0.15	-0.05	**0.76**	**0.63**	**0.25**	**0.53**	**0.37**	1.00

Bold indicated P‹

Mining the Katanga (DRC) Copperbelt: geological aspects and impacts on public health and the environment – towards a holistic approach

Thierry De Putter, Sophie Decrée
Royal Museum for Central Africa, Geology Dept, Geodynamics and Mineral Resources, B-3080 Tervuren, Belgium

Célestin Lubaba Nkulu Banza
Université de Lubumbashi, École de Santé Publique, Toxicologie et Environnement, Lubumbashi, D.R. Congo

Benoît Nemery
Katholieke Universiteit Leuven, Occupational and Environmental Medicine, B-3000 Leuven, Belgium

Abstract

The Katanga Copperbelt (Democratic Republic of the Congo, DRC) is part of a world-class copper and cobalt deposit stretching over SE DRC and NE Zambia. The Copperbelt accounts for >5% of the world's copper (Cu) reserves and ~55% of the cobalt (Co) reserves. Uranium and other trace elements are frequently associated to cobalt. Due to the "recent" (last 15 millions of years) geological history of the Katanga, Cu and Co ores were brought to the surface and are exposed in a thick cover of weathered sediments and soils. Metals (Cu, Co, and trace elements, including U) are likely to be mobilized, and to pass into surface fluids. The high cobalt content in surface sediments/soils of the Katanga Copperbelt is a unique feature, unknown elsewhere in the world. These geological factors combine with another specific aspect of the Katanga Copperbelt, i.e. the importance of artisanal and small-scale mining (ASM). Working conditions in the ASM are extremely poor, so that the diggers (locally known as "creuseurs") undergo abnormally high exposure to the metals they exploit. The consequences of this exposure on public health are currently evaluated. It is however of high importance to consider the ASM issue as a whole, with upstream economic and social components, and downstream components: fallouts on public health and environmental pollution.

Keywords. Katanga, copper, cobalt, uranium, ASM, metal load, human exposure, environmental pollution

1 Copper and cobalt deposits in Katanga

The Katanga Copperbelt is part of a world-class copper and cobalt deposit stretching over the south-eastern part of D.R. Congo and Zambia (Fig. 1). The Copperbelt accounts for >5% of the world's copper reserves, and up to 55% of the cobalt reserves (EU Raw Materials, 2010).

These Cu and Co deposits underwent a long geological evolution, from early diagenetic Neoproterozoic stratiform ore deposition (c. 820 Ma) to what is usually described as "late" remobilization episodes, in the late Cenozoic.

In the course of its 820 My-long geological history, the Cu-Co deposit underwent complex interactions with two other metal deposits:

(1) An early, c. 820 Ma (Decrée et al., in press), uranium deposit (U, V, Se, Mo, As, Ni) to the central and western parts of the province;

(2) A later, c. 450 Ma, zinc (Zn, Pb, Sn, As, Ag, Ga, In) deposit to the southeast of the province.

These three main "stocks" of elements were thus to a large extent mixed together, at least locally.

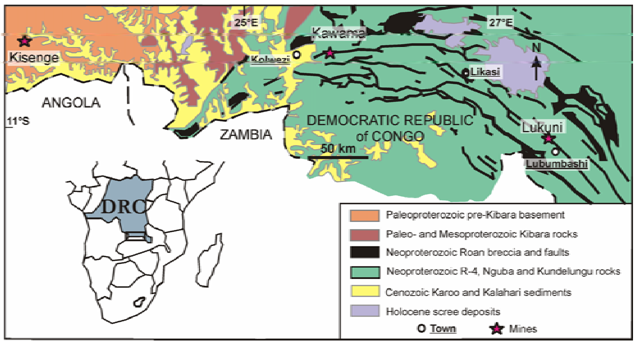

Figure 1. Schematic location and geological map of the Katanga Copperbelt.

In the Mio-Pliocene (from ~15 Ma onwards), the whole area underwent a > 500m uplift and subsequent erosion, alteration and weathering. As a result, the present-day weathered surface exposes residual accumulation of a unique series of elements, mostly combined in two main oxidized/secondary ore groups (Decrée et al., 2010).

Cu-bearing minerals/ore, typically malachite and associated mineral species, are highly diversified (De Putter et al., 2011) though generally depleted in most trace elements.

Co-bearing minerals/ores are essentially represented by heterogenite (CoOOH). This mineral acts – as do most oxyhydroxides – as a chemical "sponge", trapping many trace elements: Ni, Zn, V, As, Mo, Pb. Amongst these elements is also U, whose concentration in heterogenite may be as high as a few %. Scanning electron microscope (SEM) examination does not allow discriminating U from Co in U-rich laminated/banded heterogenite (Fig. 2): this suggests that the association between both metals is extremely intimate, either resulting from (1) true adsorption, or (2) Co^{3+}-$[UO_2]^{2+}$ substitution within the mineral structure, or (3) fine dissemination/coprecipitation of sub-micronic U compounds (UO_2?) within heterogenite.

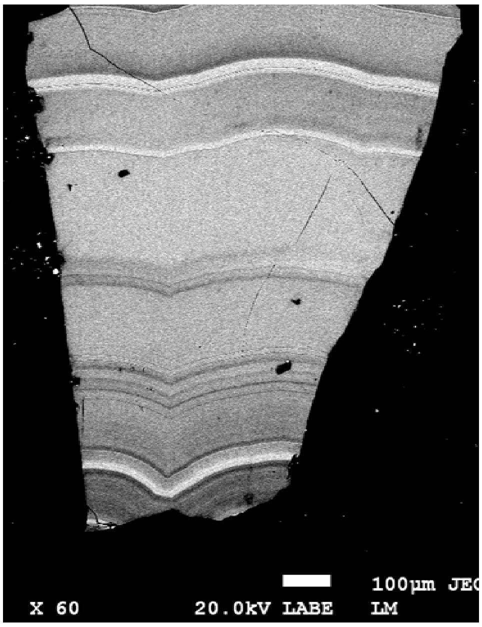

Figure 2. SEM micrograph of a U-rich (~2%) laminated heterogenite from Shinkolobwe mine (RMCA collection RGM 10816). Colour contrasts are due to the banding of the mineral and do not reflect contrasts in chemical composition.

2 Cobalt and manganese in heterogenite and the environment

The originality of the Katanga Copperbelt thus lies in the fact that high-grade Cu and Co ores are exposed in friable, weathered rocks, where they form metal-rich caps, with a definite gradient: cobalt above, copper below (Decrée et al., 2010; De Putter et al., 2010).

Within these surface ores, heterogenite has been identified as the host-mineral for many trace elements, including one notably toxic for human beings, i.e. uranium.

Thermodynamic computations show that the Eh-pH stability field for heterogenite is encountered in oxidizing conditions, and neutral to alkaline fluids (Rose, 1989) (Fig. 3). Within surface fluids in equilibrium with atmospheric CO_2 (at pH~6), heterogenite is thus likely to be destabilized, and the metal mobilized as $[Co^{2+}]_{aq}$. As soon as the fluids become less oxidizing and the pH increases, heterogenite is likely to reprecipitate, especially if no carbonates are present in the environment.

A further relevant parameter influencing cobalt behaviour in surface environment is the presence of Mn and/or Mn oxides: $[Co^{2+}]_{aq}$ may react with Mn oxides, such as to precipitate as $[CoOOH]_s$ (i.e. heterogenite) and release $[Mn^{2+}]_{aq}$ (Hem et al., 1985; Neaman et al., 2004). As Mn is always present in natural (Katangan) heterogenite, this process has to be taken into consideration in the mobilization/reprecipitation of cobalt within the mining environment in Katanga. It is also worth keeping in mind the abovementioned Co-U association and the known affinity of $[UO_2]^{2+}$ for the fluid phase, where it forms a large variety of pH-dependant complexes (Langmuir, 1978).

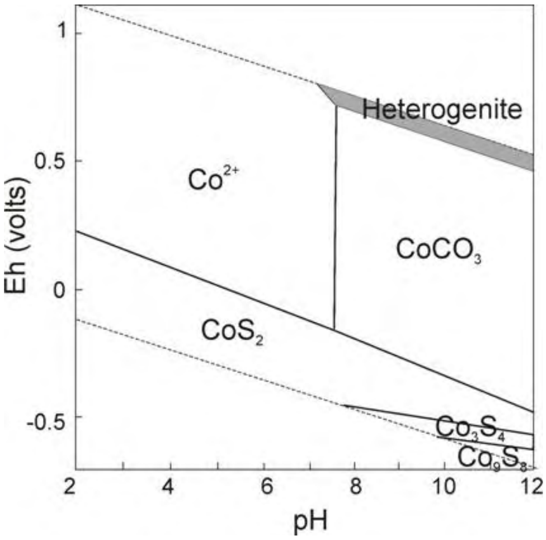

Figure 3. Eh-pH stability diagram for heterogenite (Rose, 1989).

3 Cobalt in Likasi (Shiruru) and the downstream Panda-Lufira-Tshangalele area

Chemical analyses for metal content were performed to assess whether these mechanisms are valid in the Likasi mining area and surroundings. Co ore is processed there, since many decades, in the Gecamines (GCM) Shituru facility plant, located to the south of the city centre. Waste tailings leachates are dispersed in an eastern basin connected with the Panda River. This river then flows into the Lufira River, which in turn flows in the Tshangalele Lake, and then further north. Additional well water samples were collected in Shinangwa, to the east of the lake, and in Kidimudilo, to the south of the study area (and hence regarded as a potential "blank") (Fig. 4).

Figure 4. Location map of the study area.

We routinely analysed 9 heterogenite samples from mines located in the vicinity of Likasi, 40 water samples from the abovementioned rivers, lake and wells, and we compared the obtained results with (1) the unpublished analyses of the 13H Shituru waste and its H_2O leachate (Kaniki, 2008) and (2) recently published analyses of Zambian contaminated soils (Kríbek et al., 2010).

The preliminary results we obtained on solids show two clusters of metal content patterns (Fig. 4): the high pattern of heterogenite compares fairly well with highly contaminated Zambian topsoils, the latter being however less rich in Co and Ni than the Congolese ore. The lower 13H Shituru waste pattern and its water leachate are reasonably similar to each other, though with a leachate slightly depleted when compared to the waste. Interestingly, subsurface soils from Zambia are closer to the lower pattern (waste) for Co, Ni and Cu, but closer to the high pattern (ore) for Zn and Pb.

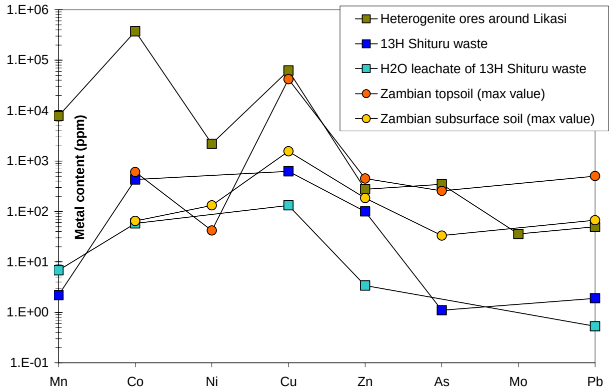

Figure 4. Metal content within analysed solids (ppm): heterogenite ores, Shituru waste and leachate, Zambian contaminated soils.

The preliminary results we obtained on fluids show that the most heavily contaminated watershed – the Panda River – has a metal pattern wholly similar in shape to the 13H waste leachate, though less concentrated by a factor 10^3 (Fig. 5). The Panda River, the Lufira River and the Tshangalele Lake display coherent enriched patterns. Their metal contents are significantly higher (by a factor 10 to 10^2) than the WHO international regulation (drinking water) for Mn, Co and Ni only.

The Mn *vs*. Co results (Fig. 6) show that cobalt logically dominates in the ore, in the waste and in its leachate. Cobalt still dominates Mn in the two rivers (Panda and Lufira) but this trend slightly reverses in the Tshangalele Lake (Mn > Co) and becomes quite obvious in the Shinangwa wells, where Mn >> Co. The same trend is observed, tough less markedly, in the Kidimudilo blank area.

These results may be interpreted in the light of the abovementioned Mn-Co affinity. Mobilized Co in surface fluids re-precipitates as heterogenite as soon as the environment becomes less oxidizing and/or more alkaline, i.e. in the swampy areas around the rivers and in/around the (shallow) lake itself.

An indirect confirmation of this hypothesis may be found in the fact that U strongly concentrates in the same areas, as indicated in an unpublished airborne total count gamma survey flown over the study area in the summer 1997. It is thus assumed that the demonstrated affinity of heterogenite for U in the ore (Decrée et al., in press) remains largely unaffected within later Co and U remobilization in surface fluids, and/or that no mechanism results in an efficient decoupling.

The mechanisms proposed in this section will be further assessed and/or confirmed in ongoing phases of this preliminary study.

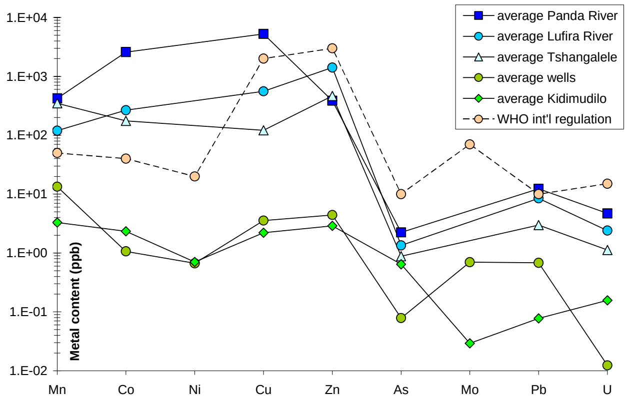

Figure 5. Metal content within analysed fluids (ppm): Panda River, Lufira River, Tshangalele Lake, Shinangwa wells and blank area (Kidimudilo).

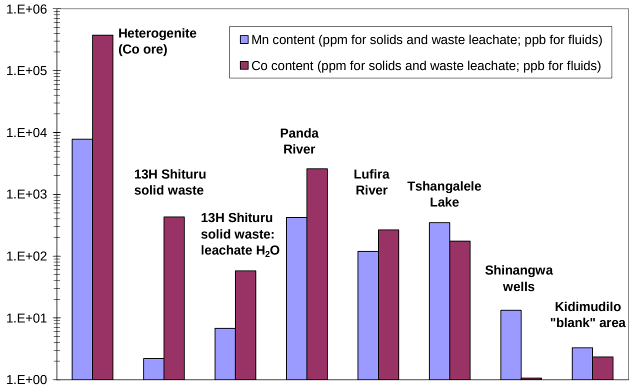

Figure 6. Mn and Co contents in solids and fluids, within the study area. Metals are more concentrated in solids than in fluids, by a factor 10^3 (ppm for solids, ppb for fluids).

4 Metal load in the environment and the issue of ASM: towards a global, *holistic* approach

The high metal load briefly described in the above section has measurable consequences for the health of people living and working in the province: Banza and co-workers (2009) analysed >350 urine samples collected in Katanga and found that: (1) for all metals (except Ni) the urinary concentrations were significantly higher in subjects from the mining area than in control subjects; and (2) the urinary Co concentrations found in this population are the highest ever reported for a general population. The authors then insisted on the fact that the pathways of exposure and health significance of these findings had to be further investigated – which is currently ongoing. This subject will be dealt with in greater detail in an associated abstract by Nemery and co-workers (2011, this IGCP 594 meeting).

The severe impact of the high metal load on human population in the Katanga Province results from a combination of two main specific features of the Katanga Copperbelt, namely: (1) its geological context (see above) and (2) the fact that the ASM sector is considerably developed in this mining district.

Current estimation of the total number of diggers ("creuseurs") for the whole province is as high as 200,000 to 250,000 (Grasser, 2010). This is not a new situation, but it is likely that current high market prices for metal commodities will drive the trend higher, as for tin in the Eastern DRC or gold in the NE of the country.

The ASM issue is definitively a complex issue, driven by economic and social parameters: unemployment and subsequent poverty leave thousands of people with no other accessible work than artisanal mining. High human exposure to metals (and especially to cobalt and uranium, as investigated above) will no doubt have short-, mid- and long-term effects on public health in the province, to say nothing of the environment – metal load, deforestation for charcoal production, etc. Hence, these effects could result in a considerable human and financial cost weighing heavily on the future development of the mining area.

To solve such a complex issue, there is obviously no simple solution. Political will to tackle the issue – at both the provincial and national levels – is an absolute pre-requisite. Redeployment of economic activities to agriculture (amongst others) is urgently needed, in a country where malnutrition is a major concern (GHI, 2010). Then come multi-donors support plans and actions, aiming at reinforcing the local expertise and capacities (such as the starting World Bank's EITI++ Promines project in DRC), e.g. in geology, earth sciences and mining management. Health and environmental monitoring precede any potential remediation policy/action plan.

All of these aspects really matter, so that it becomes obvious that an all-encompassing, global/holistic, approach will only be adequate and successful at length.

The same parameter that drives so many people in the ASM – i.e. high market prices for metal commodities – must now be urgently turned into an efficient tool fuelling broad-based development. Concurrently, better and more respectful practices in mining are clearly required in the Africa Mining Vision (African Union, 2009). Eventually, time might have come for real "win-win" partnership on natural resources. No longer "ore for infrastructure", but fair prices for ore and additional knowledge transfer and capacity building. Such partnerships, that EU should favour, would at length bring much more respect and mutual trust among the partners than most currently enforced partnerships (Decrée and De Putter, 2010; De Putter, 2012).

Acknowledgements

The authors thank the Belgian Ministry of Foreign Affairs for its financial support to the GECO (Geology for an Economic Sustainable Development) research programme.

References

African Union (2009). Africa Mining Vision: Transparent, equitable and optimal exploitation of mineral resources to underpin broad-based sustainable growth and socio-economic development, 51p

Banza Lubala Nkulu C., Nawrot T.S., Haufroid, V., Decrée S., De Putter Th., Smolders E., Kabyla Ilunga B., Luboya Numbi O., Ilunga Ndala A., Mutombo Mwanza A., Nemery B. (2009). High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. Environmental Research 109: 745-752

Decrée S, Deloule É, De Putter Th, Dewaele S, Mees F, Yans J, Marignac C (in press) SIMS U-Pb dating of uranium mineralization in the Katanga Copperbelt: constraints for the geodynamic context. To be published in Ore Geology Reviews

Decrée S, Deloule É, Ruffet G, Dewaele S, Mees F, Marignac C, Yans J, De Putter Th (2010). Geodynamic and climate controls in the formation of Mio-Pliocene world-class cobalt and manganese oxidized ores in the Katanga (DR Congo). Mineralium Deposita 45: 621-629

Decrée S., De Putter Th. (eds) (2010). Le secteur minier de la République démocratique du Congo à la croisée des chemins. Livre de résumés du Colloque International « La quête des ressources en Afrique Centrale – 2 » Tervuren, Belgique, 145p

De Putter Th. (2012). Considérations et perspectives sur l'exploitation illégale des ressources minérales dans la région des Grands Lacs et sur le « Dodd-Frank Act » américain. Cahiers Africains, Conjonctures congolaises, in press

De Putter Th, Mees F, Decrée S, Dewaele S (2010). Malachite, an indicator of major Pliocene Cu remobilization in a karstic environment (Katanga, DR Congo). Ore Geology Reviews 38: 90-100

De Putter Th, Mees F, Decrée S, Dewaele S (2011). Supergene copper deposits and minerals in the world-class SHSC deposits of the Central African Copperbelt (Katanga, DRC). 11th biennal meeting SGA 2011, Let's talk ore deposits, Antofagasta (Chile), abstract book

EU Raw Materials (2010). Annex V to the Report of the Ad-hoc Working Group on defining critical raw materials. European Commission, 220p

GHI (2010) Global Hunger Index – The Challenge of Hunger: focus on the crisis of child undernutrition. IFPRI – Concern Worldwide – Welthungerhilfe: 11-19

Grasser C (2010) Le travail des enfants dans les mines au Katanga In Decrée S., De Putter Th. (eds). Le secteur minier de la République démocratique du Congo à la croisée des chemins. Livre de résumés du Colloque International « La quête des ressources en Afrique Centrale – 2 » Tervuren, Belgique, 131

Hem J.D., Roberson C.E., Lind C.J. (1985). Thermodynamic stability of CoOH and its coprecipitation with manganese. Geochemica et Cosmochimica Acta 49: 801-810

Kampunzu AB, Cailteux JLH, Kamona AF, Intiomale MM, Melcher F (2009). Sediment-hosted Zb-Pb-Cu deposits in the Central African Copperbelt. Ore Geology Reviews 35: 263-297

Kaniki A.T. (2008) Caractérisation environnementale des rejets minéro-métallurgiques du Copperbelt congolais. Unpubl. PhD thesis Liège University, 282p

Kríbek B., Majer V., Veselovský F., Nyambe I. (2010). Discrimination of lithogenic and anthropogenic sources of metals and sulphur in soils of the central-northern part of the Zambian Copperbelt Mining District: a topsoil vs. subsurface soil concept. Journal of Geochemical Exploration 104: 69-86

Langmuir D. (1978). Uranium solution-mineral equilibria at low temperature with applications to sedimentary ore deposits. Geochemica et Cosmochimica Acta 42: 547-569

Neaman A., Mouélé F., Trolard F., Bourrié G. (2004). Improved methods for selective dissolution of Mn oxides: applications for studying trace element associations. Applied Geochemistry 19: 973-979

Rose A.W. (1989). Mobility of copper and other heavy metals in sedimentary environments. Geological Association of Canada, Special paper 36: 97-110

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

The strategic environmental management plan for the central Namib uranium province

Rainer Ellmies
Federal Institute for Geosciences and Natural Resources (BGR), rellmies@mme.gov.na

Mary Hikumuah, Kaarina Ndalulilwa & Gabi Schneider
Geological Survey of Namibia, Ministry of Mines and Energy

Abstract. The Ministry of Mines and Energy in Namibia and its cooperation partner BGR have taken the lead to conduct the worldwide first Strategic Environmental Assessment (SEA) for a mining area.

Uranium exploration has become increasingly active leading to a "uranium rush" in the central Namib desert. Besides the general positive regional and national economic impacts, there are a number of potentially conflicting social, environmental and economic aspects. The main practical issues of the SEA include water and power supply, physical and social infrastructure, health and safety, competing land uses, biodiversity and mine closure.

The SEA investigated four uranium mining scenarios with a minimum of 2 and a maximum of 12 uranium mines operational by 2020. It provides a big picture overview and sound advice on how to avoid antagonistic and negative cumulative impacts as well as how to enhance synergies or positive impacts.

To complement this process, a Strategic Environmental Management Plan (SEMP) provides an overall monitoring and management frame and practical tools for achieving best practice. The SEMP proposes ways that the operators in the industry can collaborate to achieve a common approach towards long term management and monitoring, e.g. aquifer and air quality monitoring, tailings maintenance, etc.

Keywords: uranium, environment, SEA, SEMP, Namibia

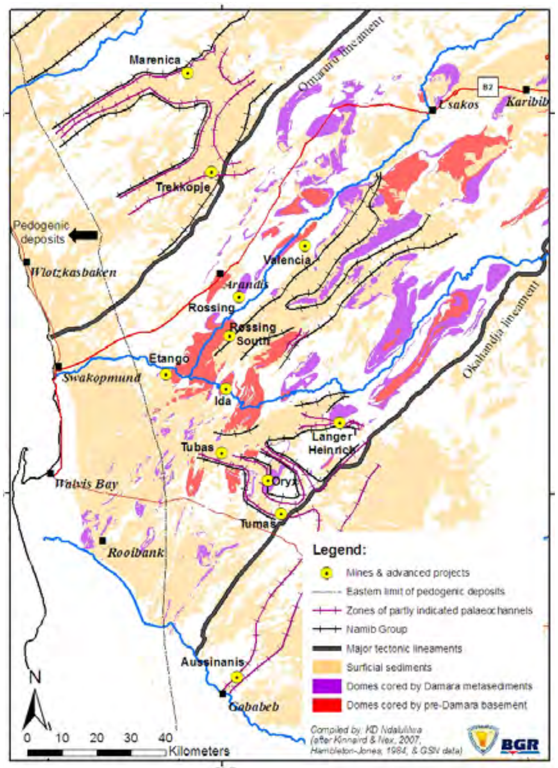

Figure 1. Uranium deposits in the central Namib uranium province and potentially uranium bearing structures.

1 Economic geology of the central Namib uranium province

Due to the rising global demand for primary supplies of uranium, exploration and mining have become increasingly active in Namibia leading to a "uranium rush". In total, the Ministry of Mines and Energy lists 78 exclusive prospecting licenses (EPLs) of which 66 have been granted and 12 are pending. Two uranium mines are currently in operation, Rio Tinto's Rössing Mine and Paladin Resources' Langer Heinrich Mine (Fig. 1). AREVA and Forsys Metals have been awarded mining licenses for Trekkopje and Valencia, respectively. Bannerman Resources at Etango and Extract Resources at Husab/Roessing South have commenced with environmental impact assessments and feasibility studies. Other companies have active exploration programs on the go.

Namibian uranium deposits are mainly confined to the high-temperature low-pressure Central Zone of the Neoproterozoic to early Paleozoic Pan-African mobile belt of the Damara Orogen, the Damara Belt. In the Central Zone of the Damara Belt, more than 300 granitic intrusions and northeast-trending dome and basin structures are known (Kinnaird and Nex, 2007). The metamorphic grade in the Central Zone increases from east to west, reaching high-grade conditions with local partial melting (Hartman et al., 1983; Jung et al., 2007). The Southern Central Zone is characterised by lithofacies differences, the presence of basement inliers and the occurrence of uraniferous granites (Miller, 1983).

Rocks of the Central Zone of the Damara Belt represent a sequence of events, starting with rifting around 850 Ma; followed by deposition of deep marine sediments; and collision of the Kalahari and the Congo Cratons marked by poly-deformation and intrusion of plutonic rocks (Miller, 2008). The Damaran intrusive rocks consist of syn- to post-tectonic granites varying in size from veins to huge plutons; emplacement of these granites happened over a period of 150 Ma, between 650 and 500 Ma (Tack & Bowden, 1999). These granites include red, medium- to fine-grained granites; coarsely porphyritic biotite monzogranites and associated dioritic rock types together called the Salem Granitic Suite; and late, fine- to coarse-grained uranium-rich pegmatitic leucogranites (Fig. 2; Smith, 1965).

Figure 2. Uranium-bearing sheeted leuco-granites intruding Khan Formation metasediments.

Uranium occurrences found in, and those coupled with, plutonic rocks offer potential for economic deposits as well as source rocks for uranium in pedogenic and sedimentary sequences (Roesner and Schreuder, 1992). The two main types of uranium deposits found in the Southern Central Zone of the Damara Belt are the sheeted leucogranite/alaskite-hosted primary uranium deposits, and the surfacial calcrete-hosted secondary uranium deposits. The known primary uranium deposits include Rössing, Husab/Rössing South, Valencia, Ida-Dome, Goanikontes, and Hildenhof, whereas calcrete-hosted secondary uranium deposits include amongst others the Langer Heinrich, Trekkopje, Aussinanis and Tubas deposits. The Rössing Uranium Mine, operated by a subsidiary of Rio Tinto PLC, is one of the largest uranium mines in the world, mining a high-tonnage, but low-grade primary ore. The deposit has been mined since 1976, and produces approximately 4000 t of uranium oxide annually (Chamber of Mines, 2008).

2 The Strategic Environmental Assessment (SEA)

2.1 Background of the Uranium SEA

A Strategic Environmental Assessment (SEA) determines the negative and positive cumulative effects of impacts on the environment, the social and economic development, and investigates and recommends ways to avoid or minimise negative or enhance positive impacts. A SEA is a tool to understand likely scenarios.

The SEA "Central Namib Uranium Rush" has been commissioned by the Ministry of Mines and Energy to investigate the impact of the uranium exploration and mining in the Erongo Region. The idea was conceived by the Ministry in collaboration with the Chamber of Mines, and the German-Namibian Technical Cooperation Project of the Geological Surveys of Germany (BGR) and Namibia (GSN).

A Steering Committee consisting of 30 members from government, NGOs, mining industry and civil society representatives guided the SEA process and the SEA working team by integrating and streamlining the SEA with existing policies, the selection of an external reviewer, ensuring public participation and examining progress of the SEA. The SEA report was completed by the end of 2010.

2.2 The SEA "Uranium Rush" scenarios

As no one can predict the future of commodity prices as well as supply and demand, the SEA had to investigate likely development scenarios:

Scenario 1 "Below expectations": Up to four uranium mines will be operational by 2020: (i) Rössing, (ii) Langer Heinrich, (iii) Trekkopje (AREVA) and (iv) Valencia;

Scenario 2 "Within expectations": Four to six uranium mines will be operational by 2020; in addition to scenario (1) (v) Rössing South Husab Mine/Extract Resources and (vi) Etango Mine/ Bannerman;

Scenario 3 "Above expectation": Up to 12 uranium mines will be operational in the region by 2020;

Scenario 4 "Boom and Bust": All the mines close suddenly and in an unplanned way.

Key statistics for Scenario 2

- **U_3O_8 production 47 Mlbs/a (2015)**
- **Export value of uranium by 2015 = N$23bn**
- **Revenue (2020) = N$2.4bn**
- **Employment peaks at 8,500 additional jobs**
  This requires:
  - plus10,000 serviced plots in nearby towns
  - schools for additional 20,000 learners by 2015
- **Water demand of the mines 35 Mm^3/a**
- **Power demand of the mines 300 MW**
- **Increase in traffic 47-72%**

Figure 3. Key statistics for the "expected" uranium rush scenario (10N$=1 Euro).

2.3 The main "issues" of the Uranium SEA

Besides the generally positive regional and national economic impact, there are a number of potentially conflicting social, environmental and economic aspects which need to be considered. Those impacts can result in strains and conflicts or opportunities and synergisms.

The main issues of the Strategic Environmental Assessment for the Central Namib Uranium Rush include:

1. Water: The operation of the 7 uranium mines (in the expected scenario) in the arid Central Namib will require approximately 35-50 million cubic meter of fresh water annually. This amount can't be extracted from the regional groundwater resources. Fresh water has to be produced by sea water desalination which is an energy intensive process. In addition, the scarce groundwater resources of the Swakop, Khan, Omaruru and Kuiseb Rivers have to be protected for any contamination from those mining operations. Therefore, the SEA established a groundwater data base for the region as well as a water balance and groundwater model (Kuells et al., 2011).

2. Power: The uranium mines will require an additional 150 to 300 megawatts of installed capacity which is currently not available.

3. Infrastructure: Pipelines, electricity lines, roads and railways have to be constructed in an optimized balance between logistics, efficiency and minimised impact to the environment. Development corridors were defined.

4. Social infrastructure: Under the expected scenario, an additional influx of approximately 50,000 people will double the number of residents in the towns of Swakopmund and Walvis Bay within a very short time. The SEA advises on regional and local town planning including housing, health facilities, recreation facilities, schools etc.

5. Health and safety: Residents in the coastal area are highly concerned about increasing radiation and its negative health effects. The SEA conducted a specialist study on air quality and radiation as baseline information and developed a regional air quality monitoring program.

6. Land use and regional economy: Mining, tourism and agriculture are Namibia's economic pillars which are in most cases antagonistically related.

7. Environment: The landscape integrity and endemic species are part of Namibia's unique natural assets. Therefore, millions of tourists visit the Namib Naukluft National Park every year and significantly contribute to the country's economy. Environmental Impact Assessments (EIA) of the mines focus on the actual mining area. However, the cumulative impacts on the environment extend these boundaries.

8. Mine closure: Mineral resources are finite resources. Therefore, mine closure and rehabilitation have to be an integral part of any feasibility study for mining operations. Although we are talking about a "rush-like" opening phase of many new mines, it is essential to develop a post-mining land use plan by now.

3 The implementation process

The Strategic Environmental Management Plan (SEMP) for the central Namib uranium province is currently being rolled out as a direct outcome of the Strategic Environmental Assessment for the Uranium Rush (SEA).

The SEMP mainstreams the sustainability principle throughout the life cycle of uranium mining related projects. It addresses the cumulative impacts of developments according to the "major issues" identified in the SEA.

The SEMP consists of 12 Environmental Quality Objectives (EQO) (Fig. 4) with 43 targets and 118 indicators. It sets targets and limits of environmental quality and acts as a score card for annual monitoring reports. Monitoring and reporting will be managed by a young and dynamic group of scientists at the Geological Survey of Namibia, the so called SEMP Office.

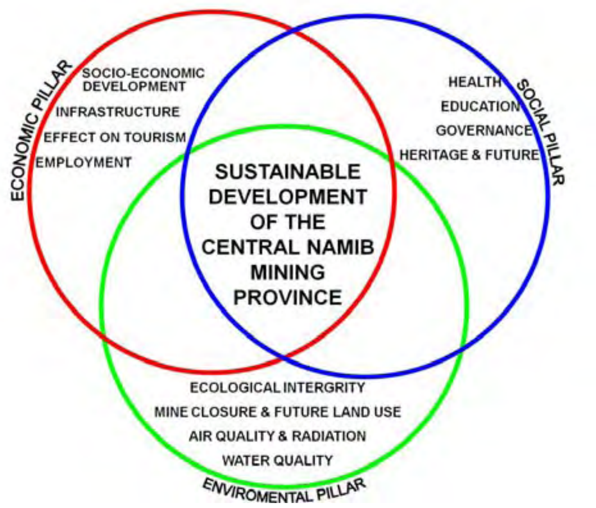

Figure 4. The 12 Environmental Quality Objectives mainstreaming the sustainable development of the central Namib mining province.

In concert with a larger skills shortage, Namibia is experiencing a critical lack of capacity in the broad environmental and biodiversity management fields, which needs to be filled through dedicated training programmes.

The Namib Ecological Restoration and Monitoring Unit (NERMU), a functional unit to be housed within the Gobabeb Training and Research Centre will be tasked with specific monitoring, research and training activities in the SEMP.

The SEA has identified a broad field of necessary additional studies and monitoring which have to be conducted within the SEMP process:

- Monitoring of radiation levels in the wider uranium province as well as at possible receptor sites, especially the major settlements (Fig. 5),

- Close monitoring of groundwater quality based on baseline data, a geohydrological model and geochemical “fingerprints” of possible effluents from the mining operations (Fig. 5),
- Developing a better understanding of the biodiversity in the Namib;
- Adopting a landscape approach to development and management of the area;
- Planning for and implementing restoration of ecosystems impacted by exploration and mining.

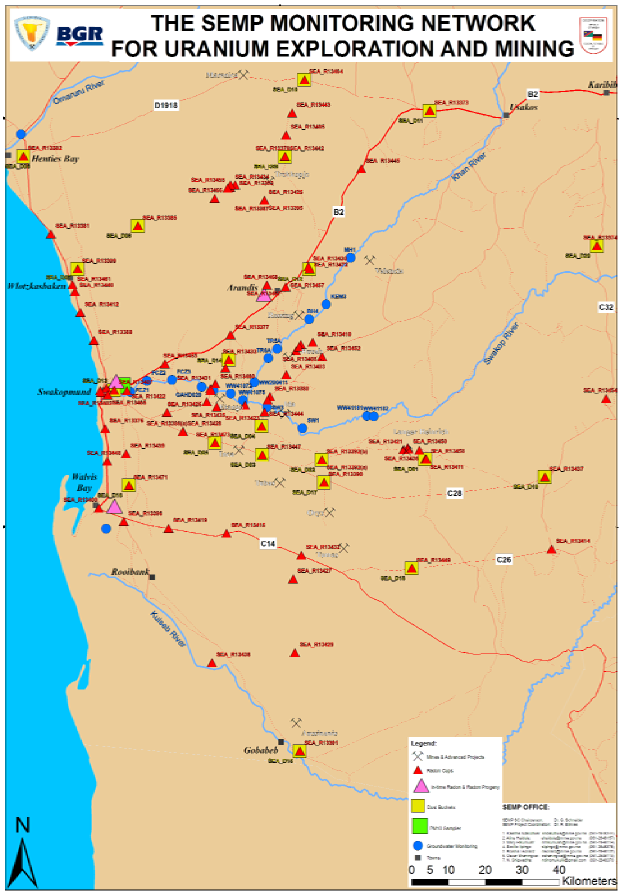

Figure 5. The SEMP network for air and water quality monitoring in the central Namib desert

Acknowledgements

The outstanding quality of the SEA “Central Namib Uranium Rush” is a direct result of the excellent work done by the Southern African Institute for Environmental Assessment (SAIEA), Windhoek, Namibia and its team of local and international experts.

References

Chamber of Mines. (2008). Chamber of Mines of Namibia Annual Review 2006-07. Windhoek, Namibia. www.chamberofmines.org.na/uploads/media/2006-07_Annual_Review.pdf

GSN/BGR (2010): Strategic Environmental Assessment of the Central Namib Uranium Rush. Ministry of Mines and Energy, Windhoek, Namibia.320p.

Hartmann, O., Hoffer, E. and Haak, U. (1983). Regional metamorphism in the Damara Orogen: Interaction of crustal motion and heat transfer, 233–241. In: Miller R. McG. (Ed) Evolution of the Damara Orogen of South West Africa/Namibia. Spec. Pub. Geol. Soc. S. Afr., 11, 515 pp.

Jung, S., Metzger, K., Hoernes, S., and Hoffbauer R. (2007). Altered mafic lower continental crust as a source for low δ^{18}O-granodiorites (Damara Orogen, Namibia)? Mineralogy and Petrology, 91, 1–10.

Kinnaird, J.A. and Nex, P.A.M. (2007). A review of geological controls on uranium mineralization in sheeted leucogranites within the Damara Orogen, Namibia. Applied Earth Science, 116, 2, 68–85.

Kuells, C., Marx, V., Ellmies, R., Bittner A., (2011). http://www.umwelthydrologie.de/media/index.php?title=Main_Page

Martin, H. and Porada, H. (1977). The Intracratonic Branch of the Damara Orogen in South West Africa. II. Discussion of relationships with the Pan-African Mobile Belt System. Precambrian Research, 5, 339–357.

Miller, R. McG. (1983). The Pan-African Damara Orogen of South West Africa/Namibia, 431-515. In: Miller R. McG. (Ed) Evolution of the Damara Orogen of South West Africa/Namibia. Spec. Publ. Geol. Soc. S. Afr., 11, 515 pp.

Miller, R. McG. (2008). The Geology of Namibia. Volume 2, Geological Survey of Namibia, Windhoek.

Roesener, H. and Schreuder, C.P. (1992). Uranium, 7.1-1-7.1-55. In: Geological Survey of Namibia. (1992). The Mineral Resources of Namibia., 1.1–1-9–17pp.

Smith, D.A.M. (1965). The geology of the area around the Khan and Swakop rivers in South West Africa. Memoir of the Geological Survey of South Africa, South West Africa Series, 3, 113.

Tack, L. and Bowden, P. (1999). Post-collisional granite magmatism in the central Damaran (Pan-African) Orogenic Belt, western Namibia. Journal of African Earth Sciences. 23, (3), 653–674.

High exposure to cobalt and other metals in mineworkers and malachite workers in Katanga, D.R. Congo

L. N. Kabamba, J. Asosa, A. Mutombo & C.L.N. Banza
Unité de Toxicologie et Environnement, Ecole de Santé Publique, Université de Lubumbashi, Lubumbashi, D.R. Congo

V. Haufroid
Laboratoire de Toxicologie Industrielle et Médecine du Travail, U.C. Louvain, Brussels, Belgium

Th. De Putter
Geology, Royal Museum for Central Africa, Tervuren, Belgium

B. Nemery
Occupational, Environmental and Insurance Medicine, Department of Public Health, K.U.Leuven, Leuven, Belgium

Keywords. Cobalt, copper, mining, child labour

1 Introduction

Southern Katanga is part of the African Copperbelt. Mining and artisanal exploitation of copper and cobalt ores are widespread, with thousands of "diggers" working in poorly regulated and dangerous working conditions.

2 Methods

We obtained spot samples of urine from three convenience samples of workers: 15 male miners (mean age 30.4 y) upon their return from work in a copper-cobalt mine, 26 informal diggers [7 men (31.4 y), 12 women (38.2 y), 7 children (12.7 y)] during their work on mine tailings and 18 artisanal workers processing malachite (54.5 y). The urinary concentrations of metals (and metalloids) were analyzed by ICP-MS.

3 Results

Median urinary concentrations (µg/g creatinine) of selected metals are shown in the Table 1

4 Discussion

The observed values are generally much higher than those found in the general population of Southern Katanga, even among people living close to mines or smelting plants (Banza et al. Environ Res 2009), and they also exceed occupational exposure limits (e.g. the ACGIH-BEI for Co is 15 µg/l). This cross-sectional study shows a high to very high occupational exposure to various metals among workers, including children, engaged in mining or processing copper or cobalt ores in Katanga. The health significance of this high exposure remains to be established.

Table 1. Median urinary concentrations ((µg/g creatinine) of selected metals

	Manganese	Cobalt	Arsenic	Uranium
Mineworkers	2.79	214.5	26.5	0.040
Diggers (children)	1.56	40.2	20.6	0.156
Diggers (adults)	1.17	26.2	13.9	0.059
Malachite workers	23.08	40.1	12.0	0.044

Environmental-geochemical survey results in the Rosh Pinah Region, Namibia

F. Kamona & B Mapani
University of Namibia, Faculty of Earth Science, Department of Geology, Private Bag 13301, Windhoek, Namibia , afkamona@unam.na

B. Kříbek, V. Majer, J. Pašava & J. Pecina
Czech Geological Survey, Geologická 6, 152 00 Prague 5, Czech Republc

F. Sibanda & A. Amkongo
Geological Survey of Namibia, Ministry of Mines and Energy

R. Ellmies
Federal Institute for Geosciences and Natural Resources (BGR)

J. Macoun & J. Keder
Czech Hydrometeorological Institute, Department of the Environment, 14306, Prague 4, Czech Republic

Abstract. Results of an environmental-geochemical survey in the Rosh Pinah Pb-Zn mine area show that dust blown from ore crushers, ore concentrate dumping grounds and the tailings dam is spread over large areas of the environment in Rosh Pinah. The dust emanating from the crusher appears to be a major environmental problem as it contains high average metal values of up to 11.1% Zn, 3.82% Pb, 0.12% Cu, 81.8 ppm As, 1.05 ppm Hg, 5 ppm Cr and 260 ppm Cd. Although the dust from the tailings dam contains relatively lower metal values (1.4–1.9 % Zn, 0.4% Pb, 638–970 ppm Cu, 0.7–2 % Mn, 54–110 ppm As, 0.15–0.22 ppm Hg, 7–16 ppm Cr, and 638–970 ppm Cu), the dust fallout from the tailings dam pose great danger to human health as it contains 25–23% of particles smaller than 10 µm on average. The dust contamination halo at Rosh Pinah is elongated towards the northwest, in accordance with the prevailing wind direction during summer. Northerly and northwesterly winds in the winter spread the dust over a larger area, particularly in the broader environs of the tailings dam. Although most of the dust is transported by wind to uninhabited mountain area, the northeastern part of Rosh Pinah and the northern section of its informal settlement are affected by the fallout tail. Apart from the dust-fallout from the tailings dam, the transport of Pb-Zn concentrates from Rosh Pinah contributes significantly to the contamination of soils along the road to Ausnek.

High concentrations of total S (up to 12 wt. %) and maximum values of As (225 ppm), Hg (1.14 ppm), Pb (43,030 ppm) and Zn (93,060 ppm) illustrate the extent of soil contamination in the uppermost part of the soil horizon in the immediate vicinity of the tailings dam. The highest concentrations of total S, Mn, Hg, As, Cd, Cu, Pb and Zn in stream sediments occur in the immediate vicinity of the tailings dam, but the heavy metal concentrations rapidly decrease downstream, and do not show any specific pattern at distances of over 300 m from the settling pond. Limited acidification of the upper soil layer exists only in the vicinity of the ore dressing plant mainly as a result of weathering of sulphide containing dust.

Water extracts from the flotation tailings are non-toxic, with contents of phenols, total and releasable cyanide, As, Cd, Hg, Ni, Pb and Se lower than permissible values valid for toxic wastes. However, water extracts from the flotation tailings may endanger the water flea (*Daphnia magna*) population whose immediate toxicity (92 to 100%) considerably exceeds the limiting value of 30%. Other species, notably aquarial fish, freshwater algae (with the exception of one sample) and seeds of vegetation have low immediate toxicity values. Heavy metal concentrations in the groundwater are low due to the near neutral (7.3-7.7) pH values of the groundwater which keep the metals insoluble. Several recommendations, including covering the slopes of the tailings pond with the grass species *Lollum pratensis* to minimise dust emissions, are provided in order to minimize the impact of mining and ore dressing operations on the local environment and human health at Rosh Pinah.

Keywords: Heavy metals, soil pollution, environment, Rosh Pinah, Namibia, tailings

Acknowledgements

The study originated within the Project of the Development Cooperation between the Czech Republic and Republic of Namibia. Interpretation of results was carried on within the IGCP/SIDA Project 594 “Assessment of impacts of ore mining and mineral processing on the environment and human health in Africa”.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Impacts of mining and processing of copper and cobalt ores on the environment and human health in the Central-northern part of the Copperbelt Province of Zambia: An overview

Bohdan Křibek, Vladimír Majer, Ilja Knésl & František Veselovský
Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic
e-mail: bohdan.kribek@geology.cz

Imasiku Nyambe
University of Zambia, School of Mines, Department of Geology, P O Box 32379
Lusaka, Zambia, e-mail: inyambe@unza.zm

Ondra Sracek
Department of Geology, Faculty of Science, Palacký University in Olomouc, Czech Republic

Vojtěch Ettler & Martin Mihaljevič
Institute of Geochemistry, Mineralogy and Mineral Resources, Faculty of Science, Charles University, Prague, Czech Republic

Abstract. Environmental-geochemical survey of the Central-northern part of the Zambian Copperbelt has revealed that air, soils, agricultural plants, stream sediments and surface waters are to various degree affected by industrial pollution. The most important sources of soil and plant contamination are gaseous emissions and dust fallout from smelters and from dry parts of tailings ponds, crushers and mining operations. Compared with areas contaminated with dust from mining operations, the gastric availability of As and Pb in areas contaminated by dust fallout from smelters is substantially higher. Concentration of metals in agricultural products (in cassava and sweet potatoes) in contaminated areas is higher compared with non-contaminated areas and increases in the range: bulb→tuber→stem→leaves. Dietary exposure to metals and arsenic through the consumption of these vegetable crops has been identified as a low risk to human health. However, surfaces of leaves are strongly contaminated by metalliferous dust in the polluted areas. As the leaves of cassava and sweet potatoes are used for vegetable salad preparation in Zambia, health risk associated with a consumption of contaminated leaves can be substantially increased by their insufficient washing. Concentration of metals in maize grains is low even in strongly contaminated areas. The most important sources of surface waters and stream sediments contamination are seepages from tailing ponds, wash out of old metalliferous slimes and outflows from chemical ore treatment plants. When the scale of mining and related activities in the Copperbelt is taken into account, the environmental impact of mining and related activities on the Kafue River is relatively limited due to a high neutralizing capacity of the mining wastes which control the rapid precipitation of iron oxides and hydroxides as well as adsorption and/or co-precipitation of copper, and cobalt.

Keywords. Soil contamination, heavy metals, cassava, sweet potato, surface water, stream sediments, Zambia, Copperbelt

1 Introduction

The issue of anthropogenic contamination of soils and plants in mining districts has been discussed in numerous reports and publications (e.g., Dudka and Adriano, 1977; Chukwuma, 1995; Barcan and Kovnatsky, 1998; Li and Thornton, 2001; Godarzi et al., 2002; Ashley et al., 2004, Kachenko and Singh, 2006). These studies were mostly undertaken on rather small areas with simple bedrock geochemistry. In large mining districts, it is generally difficult to determine the relative contributions of metals from anthropogenic and geogenic (natural) sources to the geochemistry of soil and plants based solely on the concentration of major or trace elements themselves, especially in areas with varied lithology and where both lithogenic and anthropogenic sources of contamination are present (Reimann and de Caritat, 1998).

In the case when the extent of contamination is known, the content of metals in polluted soils can be compared with their contents in a selected uncontaminated area (Reimann and Garrett, 2005).

The environmental degradation in the Zambian part of the Copperbelt is poorly quantified in spatial terms since the availability of accurate and up-to-date regional geochemical data are limited. Moreover, a high natural background of heavy metals and sulphur in many stream sediments, soils and crop plants makes the evaluation of the degree of industrial pollution difficult. To determine the extent of industrial contamination, an environmental-geochemical survey of soils, crop plants, stream sediments and surface water was carried out in the Copperbelt area of Zambia. The main objectives of the investigation were: (1) to determine the pattern of dispersal of pollutants in soils in relation to the distance from the sources of contamination, (2) to discriminate between lithogenic and anthropogenic sources of metals in soils, (3) to assess the gastric availability of metals in soils, (4) to determine the degree of contamination of agricultural plants and, (4) to identify main sources of the contamination of surface water and stream sediments.

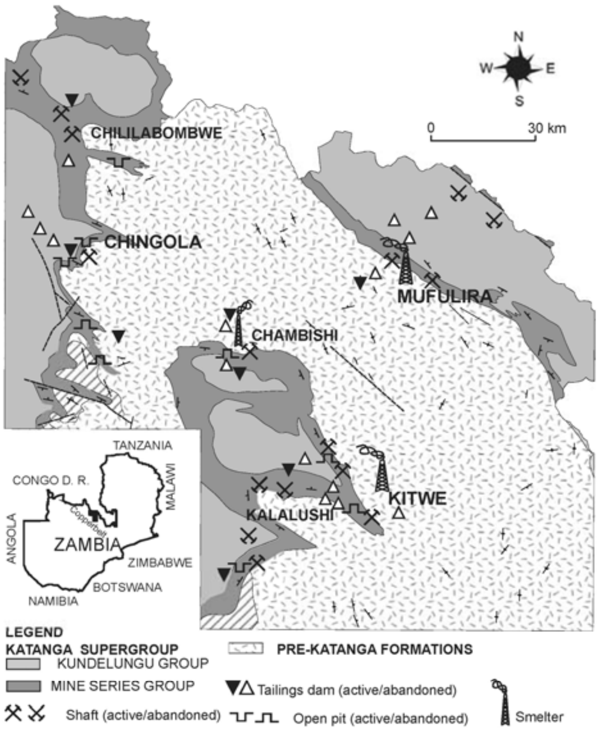

Figure 1. Geological sketch map of the surveyed part of the Copperbelt Province in Zambia showing location of major sources of contamination (After Kříbek et al., 2007).

2 Study area

The research covered 4,700 km^2 of soils in the urban and rural areas of the central-northern part of the Copperbelt Province of Zambia. The surveyed area covers 63% of the total area of the Zambian Copperbelt amounting to 7,500 km^2. The majority of the mining and mineral processing facilities and grounds of the Copperbelt (ca 92%) are located in the mapped area. Within the studied area, the largest center of population is the city of Kitwe with a total population of 866,646, then Chingola (177,445), and Mufulira (152,664). Other important towns are Chililabombwe (84,866), Kalalushi, and Chambishi. Mining activities (open pits and underground mines) are located in the vicinity of the individual towns. Smelters are located at Mufulira, Kitwe (the Nkana smelter) and at Chambishi (Fig. 1).

2.1 Mining and ore processing

The Copperbelt sediment-hosted strata-bound and stratiform deposits are characterized by finely disseminated copper-, cobalt- and iron sulphides. The principal minerals are chalcopyrite, cobalt-rich pyrite and bornite + carrolite. The host rocks include quartzite (arkose), shale and dolomite. The grades average 3 wt.% Cu and 0.18 wt.% Co in ore deposits from which both metals are extracted. Trace amounts of Au, Pt and Ag are recovered from the copper slimes during the refining process (Kamona and Nyambe, 2002).

In 2008, the annual production of copper in the whole of the Copperbelt mining district amounted to ca. 569,891 metric tons and that of cobalt was ca. 5,275 metric tons. Significant volumes of selenium (17 t) and silver (8 t) together with minor gold and platinum group elements were produced in 2008 (BMI 2009). Ores are processed by flotation at Kitwe (the Nkana ore treatment plant), Chingola, Chililabombwe, Chambishi, Chibuluma and Mufulira ore treatment plants, and for a long time were smelted and refined at the Mufulira, Kitwe and Chingola smelters. The Kitwe Smelter was decommissioned in 2008 and a new smelter was commissioned in Chingola in the same year. The Chambishi Smelter re-processes old slag from the Kitwe (Nkana) Smelter, which is rich in copper and cobalt.

2.2 Soils

According to the FAO-UNESCO (1997) classification freely drained soils of the Copperbelt can be assigned to the ferralsol group (acric, orthic or rhodic ferralsols). Ferralsols in the surveyed area are usually acid (pH$_{KCl}$: 3.94–7.15), poor in organic carbon (<0.2–7.2 wt%) and nitrogen (<0.05–1.59 wt%), and display low values of cation exchange capacity (CEC: 0.9–12.6 mmol/100g; Kříbek et al. 2010). The soils of the dambo-type (poorly drained soils, cambisols according to the FAO-UNESCO (1997) classification that occur locally along the riverbanks were not sampled.

2.3 Drainage

The drainage system in the Copperbelt area is controlled by the Kafue River, which runs first southeast and then south, following the Kafue Anticline. The most important dextral tributary rivers are the Mushishima, Musakashi, Muntimpa and Chibuluma rivers. The Kitwe region is drained by several small rivers including Mindolo, Kitwe, Uchi and Wusakile. The most important sinistral tributary rivers are the Lubengele, Mufulira and Fimpimpa rivers. Most tributary streams and rivers rise in headwater dambos (swamps). These treeless, shallow, saucer-shaped of oblong depressions cover 10 to 12% of the land surface.

3 Materials and methods of investigation

Regional environmental geochemical surveying of soil, vegetation, surface water and stream sediments was carried out using methodology recommended for the regional geochemical mapping by the FOREGS Geochemistry working group (Salminen et al., 1998). Composite surface samples were prepared by blending soil samples taken on edges and in central point of a square of 25 by 25 m in dimensions. At selected sampling points, composite samples of the subsurface soil horizon were taken from the depth of 70 to 90 cm using soil probe.

Composite samples of stream sediments were taken in an irregular network, according to the distribution and character of the drainage pattern. Composite samples were prepared by blending of four individual samples collected within the 20 m long segment of the individual streams.

To evaluate the uptake of trace metals by plants in the contaminated and non-contaminated areas of the Copperbelt, several agricultural plant species were sampled: cassava (*Manihot esculenta* Crantz, leaves and tubers), sweet potatoes (*Ipomoels batatas* sp., leaves and bulbs), and maize (*Zea mays* ssp., grains).

For the analytical determination of "total" metal and sulphur concentration in stream sediments and soils, samples were leached using a solution of concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) in the ratio 1:9 (*aqua regia* extraction). The bioaccessibility (gastric availability tests) were performed according to the US EPA (2007) protocol, identical with the Simple Bioaccessibility Extraction Test (SBET) adopted by the British Geological Survey (Oomen et al., 2002).

Samples of vegetation were burnt down in a muffle oven at the temperature of 450 ^oC. The amount of resulting ash was scaled and the metals were analytically determined in HNO_3 and HCl leachate. The results were re-calculated on dry and fresh material basis.

The chemical elements were determined in the accredited Central Analytical laboratories of the Czech Geological Survey. Fe, Co, Cr, Cu, Ni, Pb, V and Zn were determined using FAAS, As was determined by a HGAAS, and Hg was determined mercurometrically. The quality control procedure involved analysis of reagent blanks, duplicate samples and several referenced soils.

Water was sampled at the same period as stream sediments. Temperature, pH, and electrical conductivity (EC) were measured directly on-site. In the field, water samples were filtered through 0.45 μm filters and split into a subsample acidified with ultrapure HCl for determination of cations and metals and an unacidified subsample for determination of anions. Cations and metals were determined by atomic absorption spectrometry (AAS; Varian SpectraAA 280FS). Anions were determined by anion chromatography (Dionex ICS 2000). Alkalinity was determined by titration with ultrapure HCl using the Gran plot for determination of the titration end-point. In 2010, filters of 0.45 μm with retained suspension were dissolved in ultrapure HNO_3, and analyzed for total contents of selected species by inductively coupled plasma mass spectrometry (ICP MS). Results were re-calculated to mg/l for comparison with dissolved concentrations. Concentrations of anions (Cl^-, SO_4^{2-}, NO_3^-) in water were determined using high-pressure Shimadzu LC6A Liquid Chromatograph. Cations in water were determined by means of ICP MS in Acme Analytical Laboratories, Vancouver, Canada. Statistical characteristics of analytical data were obtained using the S-plus non-parametric statistical programme (MathSoft, USA).

4 Results and discussion

The environmental-geochemical survey in the Copperbelt identified a broad range of effects mining has on the environment and specific impacts of mining on terrestrial system and river drainage pattern. These are presented and discussed in the following overview of mining and mineral processing activities in the Copperbelt and their impacts.

4.1 Sources of contamination

The main sources of contamination related to ore mining and processing include:

- Open-cast operations: Open-pit mining generates a high tonnage of waste rocks and overburden which is disposed of in waste dumps, overburden dumps and waste rocks dumps that represent an important source of dust fallout. Because of their interaction with exposed ores, pit waters are usually of poor chemical quality, with high dissolved copper and cobalt concentrations. Their disposal thus poses a potential hazard to groundwater and surface drainage.
- Ore crushers: The dust from crushers in Mufulira contains, for example, 39,100 ppm of copper, 12 ppm of cobalt, 20 ppm of lead and 1.2 ppm of arsenic.
- Production of ore concentrates: The employed technology allows spillage of suspensions from thickeners and pipelines. A part of suspensions is drained into streams, producing strong chemical and mechanical contamination of stream sediments (siltation).
- Washing of old flotation tailings and their sedimentation in retention basins, from which they are pumped out to the chemical dressing plants for acid leaching is associated with overflows of the suspensions to rivers due to insufficient capacity of retention basins. These suspension contain up to 1600 ppm Cu, 450 ppm Co, 15 ppm As, 12 ppm Pb and also increased concentrations of bismuth, cadmium, mercury and zinc.
- In the past, transport of ore concentrate from Chingola Processing Plant to Nkana Smelter significantly contributed to the contamination of soil and plants along the road and railway from Chingola to Kitwe.
- Tailing impoundments: Dry sections ("beaches") of these tailing ponds are source of dust fallout that can be seen on plant leaves to a distance of a few kilometers from the source of pollution. The dams of tailing impoundments are leaking in several places, which leads to discharge of pulp giving rise to precipitates rich in iron. The contents of Cu in these precipitates vary between 800 and 2500 ppm, Co between 780 and 1900 ppm, As 2.7 up to 350 ppm, and Pb 14 up to 270 ppm.
- Smelters: Emissions of sulphur oxides from smelters in nearby residential areas contain on average up to 125 μg SO_2 m^{-3} of air (Zambian guideline limit: 50 μg $SO_2.m^{-3}$). Emissions of SO_2 from the Copperbelt smelters ranged from between 300,000 and 700,000 in the past (ZCCM, 2002). Suspended particles contain as much as 0.108 μg Cu, 0.008 μg of Co, 1.09 μg of Zn, 0.498 μg of Pb per m^{-3} of air and a range of other toxic metals (Hg, Bi, Sn). At present, modernization of old smelters and commissioning of new ones substantially reduced health hazard related to atmospheric pollution in the Copperbelt.

4.2 Contamination of terrestrial systems

4.2.1 Contents of metals and sulphur in surface and subsurface soils

The contamination of terrestrial systems (soil and vegetation) is mostly ascribed to dust fallout. The concentration of copper in soils near smelters and tailing ponds attain as much as 41,900 ppm, that of cobalt 606 ppm, zinc 450 ppm, arsenic 255 ppm and mercury 8.2 ppm (Table 1). In order to distinguish natural concentrations of metals in soils from those ascribed to contamination by dust fallout, soil sampling was undertaken at two depth horizons: first, the surface soil (topsoil) which is most affected by dust fallout and, secondly, a reference soil horizon at a depth of 80–90 cm.

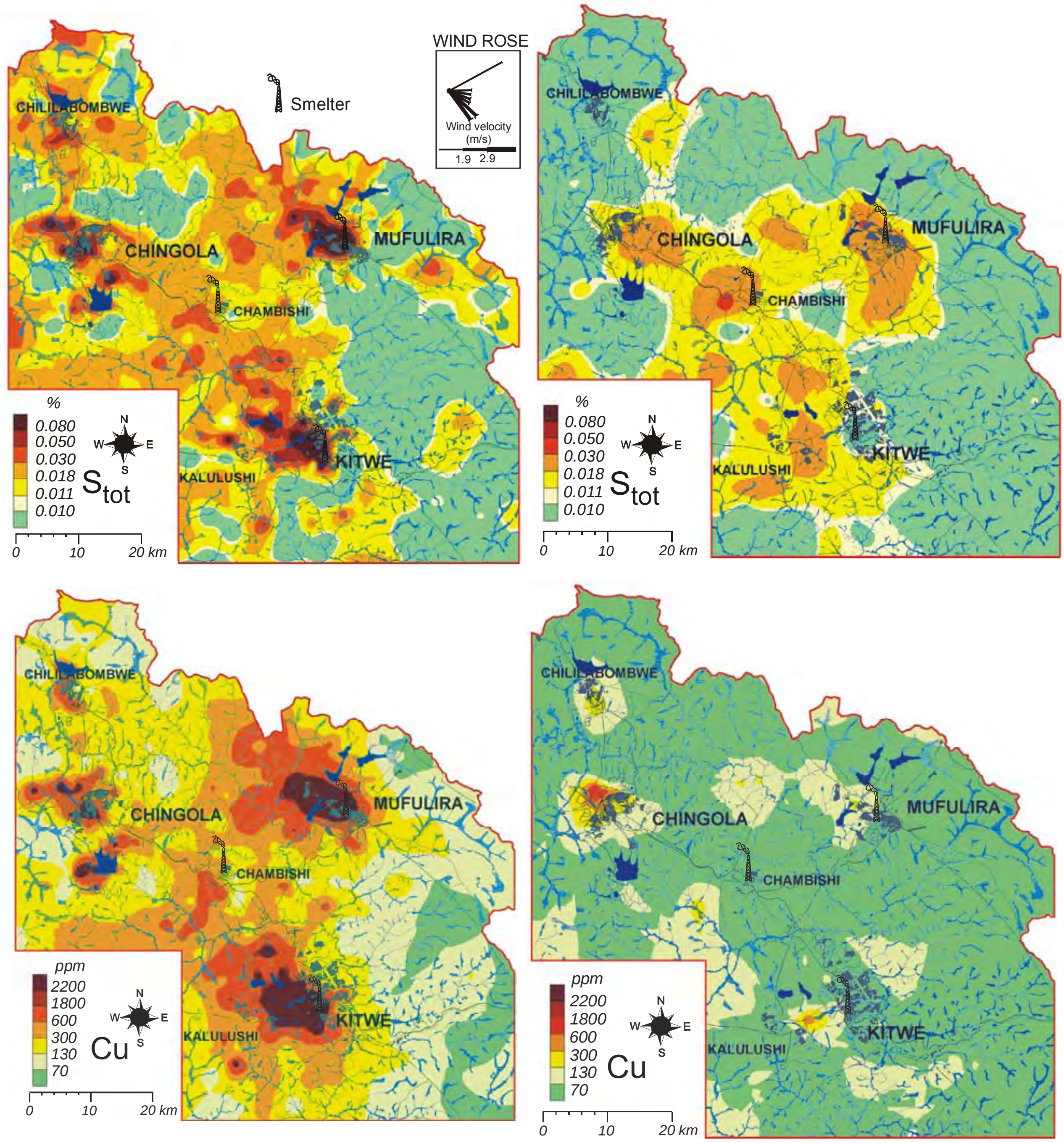

Fig. 2. Distribution of total sulphur (S_{tot}) in topsoil (A) and in subsurface soil (B), and distribution of copper in topsoil (C) and in subsurface soil (D) in the surveyed area of Copperbelt.

Here, the subsurface soil is believed to represent the natural geochemical background. The content of S_{tot}, Cu, Co, Cu and Hg are higher in the topsoil compared to subsurface soil (Tables 1 and 2). Maximum values of S_{tot} (Fig. 2A,B) Cu (Fig. 2C,D) in the topsoil are characteristic of areas strongly affected by dust fallout from smelters and tailings ponds.

In contrast, the medians of Fe, V, Cr and Ni are higher in subsurface soils, which indicate their geogenic (natural) origin (Table 1 and 2). The only exceptions are the elevated contents of nickel detected in the close vicinity of smelters. The map of surface soil to subsurface soil cobalt contents ratio (Fig. 3) clearly demarcate areas with heavy contamination of surface soils (shown in red) from those with naturally increased cobalt values in soils, which are shown in green on the Figure 3. A narrow corridor of contamination between Chingola and Chambishi indicates soil topsoil contamination due to concentrate transport from Chingola Processing plant to Nkana Smelter in Kitwe.

Table 1. Median, minimum and maximum values of variables in surface soils of the Zambian Copperbelt

	Surface soil		
Variable	Min. value	Median	Max. value
pH	3.56	4.88	9.17
S_{tot} (wt.%)	<0.01	0.02	1.42
Fe (wt.%)	0.10	0.97	7.13
As (ppm)	<0.10	0.46	254.90
Co (ppm)	<5	10	606
Cr (ppm)	1.6	16	595
Cu (ppm)	15	289	41,900
Hg (ppm)	0.002	0.014	8.2
Ni (ppm)	<5	<5	42
Pb (ppm)	<10	<10	21
V (ppm)	<10	21	52
Zn (ppm)	<5	13	450

Table 2. Median, minimum and maximum values of variables in subsurface soils of the Zambian Copperbelt

	Subsurface soil		
Variable	Min. value	Median	Max. value
pH	3.91	4.27	7.12
S_{tot} (wt.%)	<0.01	<0.01	0.04
Fe (wt.%)	0.47	2.58	13.1
As (ppm)	<0.1	0.47	33.20
Co (ppm)	<5	5	65
Cr (ppm)	20	54	256
Cu (ppm)	6	35	1560
Hg (ppm)	<0.002	0.009	0.072
Ni (ppm)	<5	15	132
Pb (ppm)	<10	<10	67
V (ppm)	<10	56	330
Zn (ppm)	<5	13	185

Generally, the extent of anthropogenic contamination of surface soils can be expressed using the *Enrichment Index* (EI, Kříbek et al., 2010) The EI is based on the average ratio of the actual and median concentrations of the given contaminants:

$$EI = \frac{\left(\frac{As}{m_{As}} + \frac{Co}{m_{Co}} + \frac{Cu}{m_{Cu}} + \frac{Hg}{m_{Hg}} + \frac{Pb}{m_{Pb}} + \frac{Zn}{m_{Zn}}\right)}{6}$$

where *m* is the median value of concentration for a given metal in surface soil (topsoil).

The *Enrichment Index* actually reflects a higher-than-median or lower-than-median average content for the six elements in surface soils of the Zambian Copperbelt. Areas with EI >1 are in this contribution reported as contaminated by industrial activities, especially by ore mining and processing. Areas with EI<1 are reported as non-contaminated (Fig. 4).

The concentrations of trace metals in soils in the surveyed area were compared with the Canadian soil quality limits for trace elements (Canadian Environmental Council of Ministers of the Environment - CCME, 2000). The Canadian guidelines for soils have different levels for agricultural, development, commercial and industrial land uses (Table 3). Limits for trace elements in soils in Canada are given in Table 3. Canadian soil quality guideline values for trace metals for agricultural, development, commercial and industrial land uses (in ppm, CCME 2000). Proportion of samples exceeding the Canadian limits in the topsoil in surveyed area of the Copperbelt are given in Table 3 in parentheses.

Table 3. Canadian soil quality guideline values for trace metals for agricultural, development, commercial and industrial land uses (in ppm, CCME 2000). Proportion of samples exceeding the limits in the topsoil of the surveyed area of the Copperbelt is given in parentheses.

	Risk elements Priority No. 1		Risk elements priority No. 2			No. 3
Element/ Land use	Pb	Hg	As	Cu	Zn	Co
Agricultural	70 (1.6%)	6.6 (0%)	12 (0.8%)	63 (66%)	200 (0.6%)	20 (22.8%)
Development	140 (0.8%)	6.6 (%)	12 (0.8%)	63 (66%)	200 (0.6%)	20 (22.8%)
Commercial	260 (0.8%)	24 (0%)	12 (0.8%)	100 (58%)	380 (0.4%)	250 (1.5%)
Industrial	400 (0.8%)	30 (0 %)	12 (0.8%)	100 (58%)	380 (0.4%)	250 (1.5%

4.2.2 Factor analysis of topsoils

Four main factors (with a sum of squares loading >1) explain 69.4% of the total variance of the data set for topsoils. The factor matrix after varimax rotation of the components in topsoils shows a grouping of Cr, Zn, Pb and As into the first component (F1; accounting for 17.7 % of variance), Cr, Ni and Fe are grouped into the second component (F2; 16.5 % of variance) S_{tot}, Co, Cu and Hg are grouped into the third component (F3; 13.7 % of variance) pH, C_{carb}, Co and Ni in F4 (11.7 % variance) and, C_{org}, Zn, Pb, and Hg in F5 (9.9 % variance).

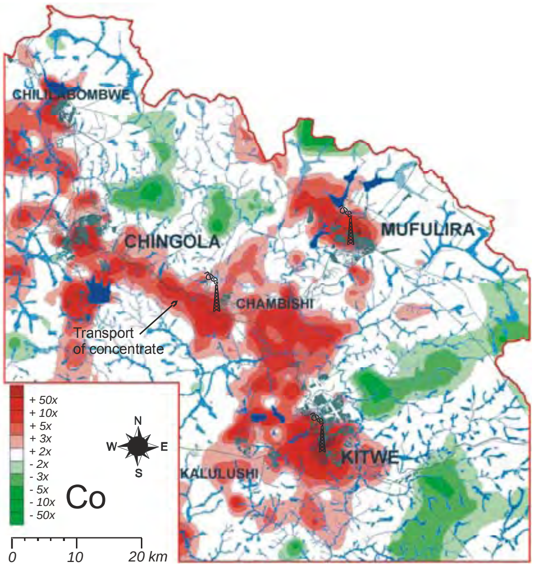

Figure 3. Contour map of ratio of cobalt in topsoil to subsurface soil.

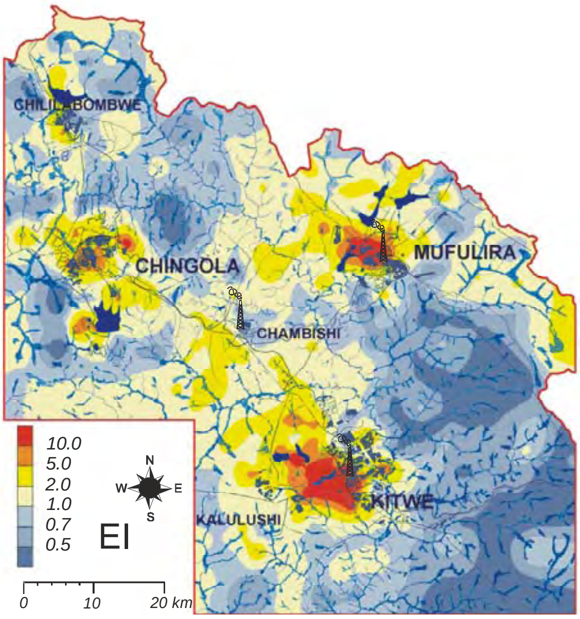

Figure 4. Contour map of the *Enrichment Index* in topsoils of the surveyed part of Copperbelt.

The procedure of factor analysis enables a calculation of factor scores, which then replace the values of original variables. As an example, positive anomalies reaching factor scores >1 in the F1 to F4 score map for topsoils, are plotted in Figure 5.

(1) Score values of >1 for Factor 1 (Fig. 5A), demarcate a small area NW of the Nkana industrial complex in Kitwe (in the direction of the prevailing winds). This complex, comprising a flotation ore treatment plant for and a smelter, also stockpiles old slags from the Kitwe smelter for crushing and re-melting in the smelter at Chambishi. These slags are highly enriched in chromium relative to the ore concentrate because this metal is concentrated in the silicate melt during the smelting process. Therefore, Factor 1 is designated as “slag-specific” and high values of the factor score are interpreted as being due to fallout of dust from the slag treatment plant.

(2) Areas with high scores for Factor 2 are mostly confined to lithologies formed by the Katanga Supergroup (Fig. 5B). This factor is designated as “bedrock (soil)-specific” and can be interpreted as resulting from the accumulation of these metals in soils formed by fast weathering of the slightly metamorphosed or non-metamorphosed Katanga Supergroup rocks.

(3) Factor 3 reflects anthropogenic influence. The highest values of this factor score demarcate the environs of the smelters at Mufulira and Kitwe (Fig. 5C). On the other hand, the values of the scores for this factor in the neighbourhood of the smelter at Chambishi are low because old slags low in sulphur are remelted at this smelter. Consequently, Factor 3 is marked as “smelter-specific”, and high values of this factor score are ascribed to emissions from smelters processing sulphide concentrates.

(4) Areas with high factor scores for Factor 4 occur in the close vicinity of large flotation tailing dams (Fig. 5D). The only exception is the tailing dam north of Mufulira where waste from the extraction of copper ores confined to sandstones was stockpiled. These ores are very poor in carbonates. Therefore, Factor 4 is interpreted as a result of dust fallout from tailing dams containing flotation wastes with a higher content of carbonate or from tailing dams where flotation waste is stabilized by added carbonates. This factor is then designated as “tailings-specific”.

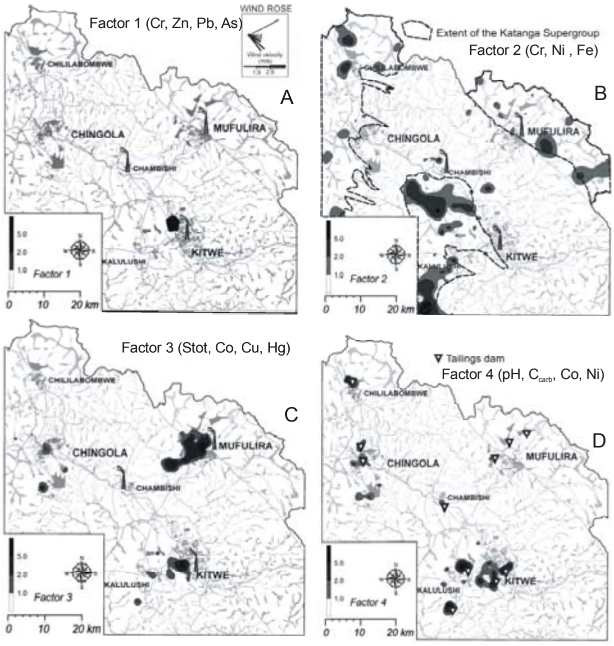

Figure 5. A contour map of factor score (>1) of factor 1 (slag-specific; A), factor 2 (bedrock-specific; B), factor 3 (smelter-specific; C) and factor 4 (tailings-specific; D) of the Copperbelt, Zambia.

4.2.3 Gastric availability of metals in surface soils

The assessment of gastric availability of metals in contaminated soil is prerequisite for the evaluation of health risks as well as prerequisite for the success of remediation works. To assess health risk associated with toxic metals-rich dust fallout or consuming of unwashed or poorly washed agricultural products from contaminated areas, the test of gastric availability of metals is frequently employed. The test is based on the modelling of the decomposition of metals in gastric juice (Davis et al., 1992, 1996). To model the reaction of metals with gastric juice, the suspension of acidified solution of glycine and soil or dust sample is shaken for two hours at the temperature of 38 °C to simulate the dwelling of contaminated material in stomach. Results of the gastric available (glycine/HCl extraction) part of metals, expressed in percent of their total concentration (*aqua regia* extraction) in topsoils in the Nkana Smelter and the Chingola Mining areas are plotted in Tables 4 and 5.

Based on the results of leaching experiments, the gastric availability and therefore the toxicity of metals increases in the range: Fe → As → Pb → Zn → Co → Cu in the Chingola Mining area.

Table 4. Median concentration of total metals (*aqua regia*, Median T) and median concentration of gastric available metals (Median G) in the Nkana Smelter area, and the amount of gastric available metals expressed in percents of total metal concentration in soil (R %).

	Nkana Smelter area		
	Median T	Median G	R %
As	2.91	0.86	29.6
Co	90	32	36
Cu	2027	1190	59
Fe	1.52	0.04	2.6
Pb	30	24	80
Zn	44	19	43

Table 5. Median concentration of total metals (*aqua regia,* Median T) and median concentration of gastric available metals (Median G) in surface soils in the Chingola Mining area, and the amount of gastric available metals expressed in percents of total metal concentration in soil (R %).

	Chingola mining area		
	Median T	Median G	R %
As	0.81	0.04	4.9
Co	18	7	38.
Cu	457	223	49
Fe	1.43	0.03	2.1
Pb	20	4	20
Zn	24	9	38

In the Nkana Smelter area, the gastric availability increases in the range: Fe → As → Co→ Cu → Zn → Pb. The bioavailability of As and Pb in the smelter area is substantially higher compared with the area polluted only by dust from mining operations. Difference in metals gastric bioavailability can be explained as due to coarse character of dust particles in the mining area and fine character of dust fallout from smelter.

4.2.4 Metals in plants

The contents of metals and arsenic in the leaves and tubers of cassava (*Manihot esculenta*) and sweet potatoes (*Ipomoea batatas*) growing on uncontaminated and contaminated soils of the Zambian Copperbelt mining district have been analyzed.

In order to assess the distribution of metals also in other parts of both vegetables a few samples of the same plants were taken in uncontaminated parts of the Copperbelt, from which leaves, leaf stalks, stems, tubers and roots were analysed. Concentration of metals in cassava and sweet potatoes increases in the range: tuber, root→stem→leaf stalk →leaf. The contents of copper in cassava and sweet potato leaves growing on contaminated soils reach as much as 612 mg kg^{-1} Cu (total dry weight [dw]) and 377 mg kg^{-1} dw of Cu respectively. The contents of Cu in leaves of both plants growing on uncontaminated soils are much lower (up to 252 and 198 mg.kg^{-1} Cu respectively). The contents of Co, As and Zn in leaves of cassava and sweet potatoes growing on contaminated soils are higher compared with uncontaminated areas, while the contents of Pb do not differ significantly (Fig. 6). The contents of analyzed chemical elements in the tubers of both plants are lower than in their leaves with the exception of As. Differences in contents of Cu, Zn, Co, Pb and As in tubers of plants growing on contaminated and uncontaminated soils are small. Even in strongly contaminated areas, the contents of copper in the leaves and tubers of both vegetables do not exceed the daily maximum tolerance limit of 0.5 mg.kg^{-1}/human body weight (HBW) established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA). The highest tolerable weekly intake of 0.025 mg kg^{-1} /HBW for lead and the highest tolerable weekly intake of 0.015mg.kg^{-1}/ HBW for arsenic are exceeded slightly in a few samples. The excess in these limits of tolerance for arsenic and lead is evidently not only due to industrial contamination but also to the naturally high contents of both elements in the soils of some areas in the Copperbelt mining district. Therefore, dietary exposure to metals and arsenic through the consumption of these vegetable crops has been identified as a low risk to human health. Nevertheless, as the surfaces of leaves are strongly contaminated by metalliferous dust in the polluted areas (Fig. 7), there is still a significant risk of ingesting dangerous levels of copper, lead and arsenic if dishes are prepared with poorly washed foliage. Contents of metals in superficially and thoroughly washed cassava and sweet cassava leaves from the area of the Mufulira Smelter for example, are given in Table 6. It follows from this table that insufficient washing can substantially increase an uptake of metals during consuming of vegetable salads.

Compared with leaves of cassava and sweet potatoes, content of metals in grains of maize is very low and does not differ significantly in contaminated and uncontaminated areas.

Table 6. Concentration of metals in slightly and thoroughly washed leaves of sweet potato growing at the vicinity of the Nkana Smelter in Kitwe. Concentration in µg.g^{-1} on dry weight.

Element	Slightly washed leaves MED ± MAD	Thoroughly washed leaves MED ± MAD	% of element removed
As	0.08 ± 0.01	0.07 ± 0.01	12.0
Co	1.30 ± 0.05	0.60 ± 0.03	53.8
Cu	35.95 ± 5.74	20.12 ± 1.12	44.0
Fe	800.20 ± 51.0	183.00 ± 0.0	77.1
Pb	0.71 ± 0.11	0.61 ± 0.11	14.3
Zn	345.20 ± 6.16	316.27 ± 4.43	8.4

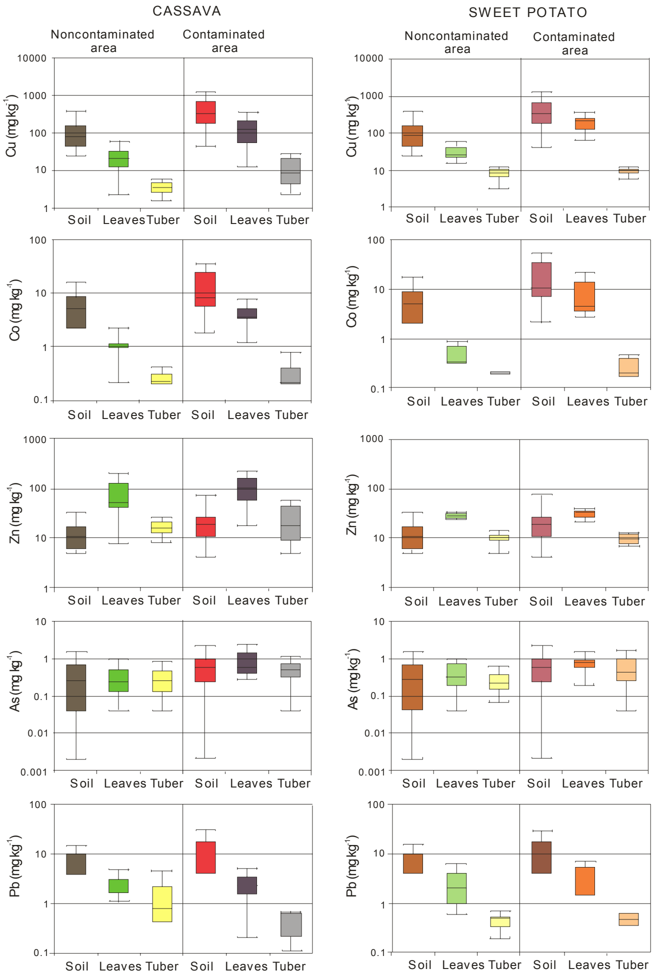

Fig. 6. Statistical distribution (box-plots) of Cu, Co, Zn, As and Pb contents in soil, cassava and sweet potato leaves and peeled tubers from uncontaminated and contaminated areas of the Zambian Copperbelt. Contents of metals and arsenic in plants are expressed in dry weight. Extreme values (outliers) are ignored.

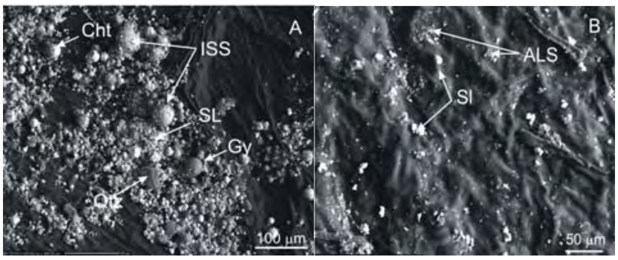

Figure 7. Dust fallout particles on the surface of cassava leaves from contaminated area of the Zambian Copperbelt. A: Cassava leaves collected 1 km downwind of the Mufulira Smelter. Dust particles are composed of angular and subangular grains of quartz (Qtz), spherical grains of Cu-Fe-S intermediate solid solution (ISS), chalcanthite (Cht), gypsum (Gy) and clusters of fine-grained slag particles (Sl). B: cassava leaves taken 4 km downwind of the smelter. Dust particles consist of clusters of very fine alumosilicate particles (ALS) and particles of slag (Sl) with detectable amount of copper, bismuth, zinc and lead.

4.3 Contamination of stream sediments and surface water

Contamination of the Kafue River network in the Copperbelt, northern Zambia, was investigated using sampling and analyses of solid phases and water, speciation modelling, and multivariate statistics. Total metal contents in stream sediments show that the Kafue River and especially its tributaries downstream from the main contamination sources are highly enriched with respect to Cu and exceed the Canadian limit for freshwater sediments (Table 7).

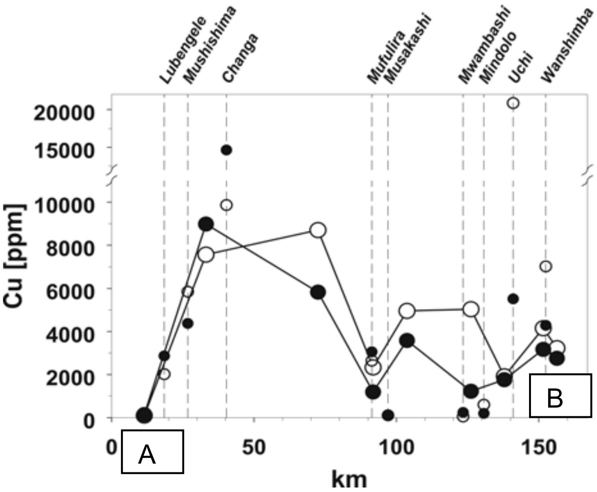

Figure 8. Contents of copper in stream sediments of the Kafue River and its tributaries in years 2009 (empty circles) and 2010 (full circles). Symbols on verical lines indicate contents in tributaries. A: Kafue River inflow to the Copperbelt Mining Area. B: Kafue River outflow from the Copperbelt Mining Area.

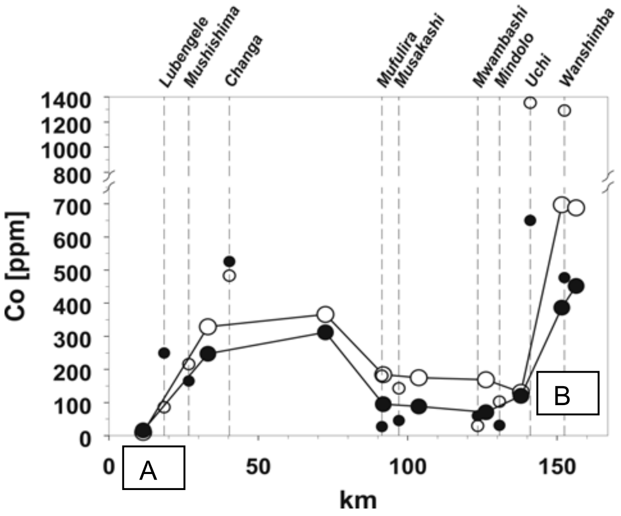

Figure 9. Contents of cobalt in stream sediments of the Kafue River and its tributaries in years 2009 (empty circles) and 2010 (full circles). Symbols on verical lines indicate contents in tributaries. A: Kafue River inflow to the Copperbelt Mining Area. B: Kafue River outflow from the Copperbelt Mining Area.

Total Cu and Co contents recorded in stream sediments in 2009 and 2010 are provided in Figures 8 and 9. It follows from Figures 8 and 9 that the main sources of the Kafue River stream sediment contamination are tributaries in the Chingola and Kitwe areas.

Values of electrical conductivity (EC) of surface water, which correspond to total mineralization are shown in Figure 10. In the Kafue River they increased from 128 µS/cm at the inflow of the Kafue to the Copperbelt Industrial Area) to 423 µS/cm in the outflow sample.

Values of pH in the Kafue River and its tributaries are alkaline in the contaminated area (Table 8) and concentrations of sulphate, which behaves conservatively, gradually increase downstream. There is a significant input of Cu and Co from multiple contamination sources close to the town of Chingola, located on the Mushishima tributary, but both metals are bounded to suspended particles (accounting for more than 95% of the total contaminant load), which settle in the Kafue River (Figs. 11 and 12). Additional contaminant sources such as the Uchi mine tailings and Nkana industrial complex are located in the industrial area around Kitwe but metals released from these sources are mostly found in suspension. Nevertheless, the concentration of dissolved cobalt, copper, and in some places of manganese, selenium and sulphates in surface water of the most contaminated tributaries of the Kafue River exceed the Zambian Emission limits for these compounds (Table 8).

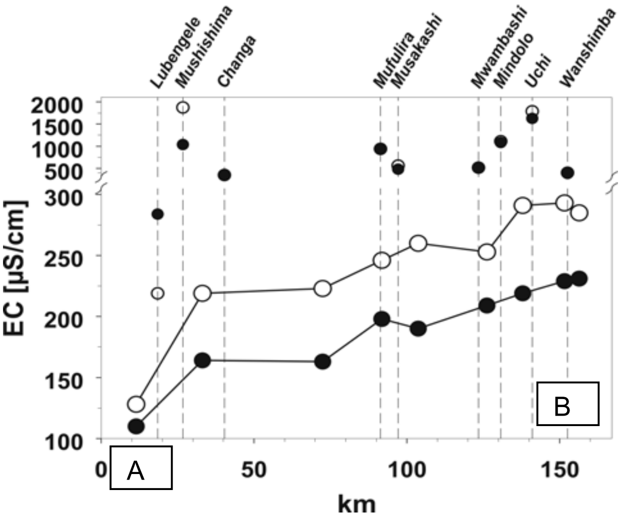

Figure 10. Values of electrical conductivity of surface water of the Kafue River and its tributaries. Full circles-dissolved concentrations in 2010, empty circles-dissolved concentrations in 2009. A: Kafue River inflow to the Copperbelt Mining Area. B: Kafue River outflow from the Copperbelt Mining Area.

Water balance based on sulphate indicates, however, that the inflow from the most contaminated tributaries is less than 4 % of total discharge in the Kafue River.and therefore, dissolved metals are attenuated efficiently, thus the resulting in their relatively low concentrations at the Kafue River outflow from the Copperbelt.

Speciation modelling suggests a possibility of precipitation of some Cu phases in the most contaminated tributaries such as Mushishima. When the scale of mining and related activities in the Copperbelt is taken into account, however, the environmental impact of mining and related activities on the Kafue River is relatively limited due to a high neutralizing capacity of the mining wastes which control the rapid precipitation of iron oxides and hydroxides as well as adsorption and/or co-precipitation of copper, and cobalt. The high metal content in stream sediments, however, may pose a potential environmental risk during accidental acid spikes, when significant fractions of metals in sediments can be re-mobilized.

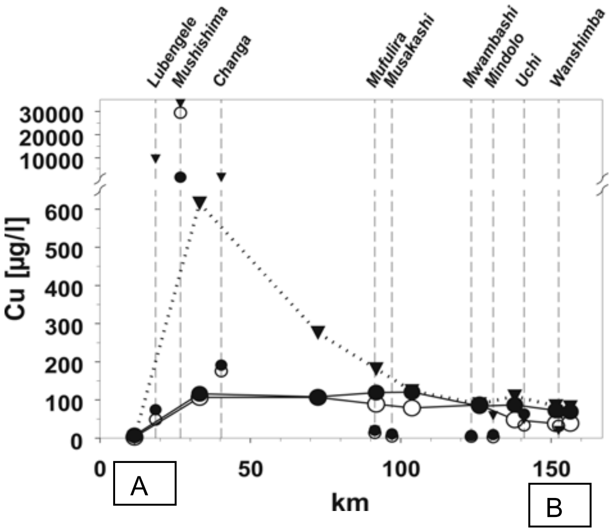

Figure 11. Values of copper of surface water of the Kafue River and its tributaries. Full circles-dissolved concentrations in 2010, empty circles-dissolved concentrations in 2009, full inverted triangles-concentrations in suspension in 2010, symbols on vertical lines indicate concentrations in tributaries. A: Kafue River inflow to the Copperbelt Mining Area. B: Kafue River outflow from the Copperbelt Mining Area.

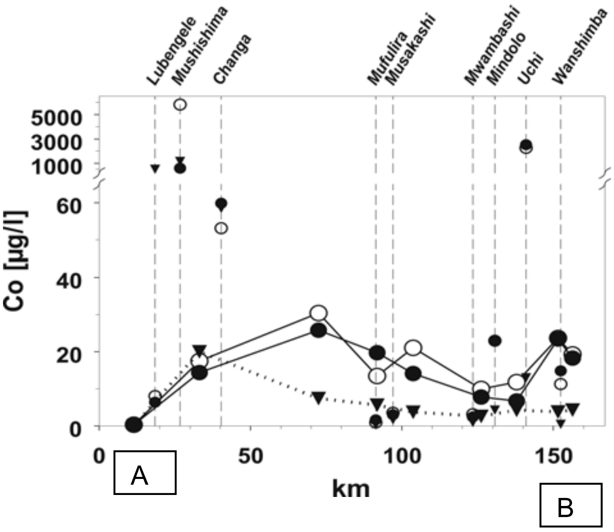

Figure 12. Contents of cobalt in stream sediments of the Kafue River and its tributaries in years 2009 (empty circles) and 2010 (full circles). Symbols on vertical lines indicate contents in tributaries. A: Kafue River inflow to the Copperbelt Mining Area. B: Kafue River outflow from the Copperbelt Mining Area.

Table 7. Concentration of total sulphur (S_{tot}) and trace elements in sediment of the Kafue River catchment (Min – Max. values) in the Copperbelt area, Zambia. Canadian Limits for fresh-water sediments according to the Regulation No. CCME-EPS-98E (CCME, 2000) are given for comparison.

S_{tot} (wt.%)	As (ppm)	Hg (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Mn (ppm)	Ni (ppm)	Pb (ppm)	Zn (ppm)
Concentration of total sulphur and trace elements (Min. - Max. values) at the Kafue River inflow to the industrial Copperbelt Area									
0.07–0.08	0,14–-0.57	0.02–0.03	17–21	47–81	115–161	103–131	18–36	4–13	45–80
Concentration of total sulphur and trace elements (Min - Max. values) of the contaminated Kafue River tributaries, Copperbelt Area									
0.14–1.24	0.04–116.1	0.007–1.13	34–1427	27–90	69–19,490	131–12,790	8–186	4–160	13–170
Concentration of total sulphur and trace elements (Min - Max. values) at the Kafue outflow from the Copperbelt Area									
0.14–0.15	5.52–2.01	0.07–0.14	350–731	35–45	1520–3204	1654–2849	15–31	15–34	38–73
Canadian environmental limits for fresh water sediments									
	17	0.486	220	90	197			91.3	315

Table 8. Physical properties and concentration of selected elements (Min. – Max. values) in surface water of the Kafue River and its contaminated tributaries. Zambian limits for effluent discharged to surface water and Czech and EU standards for surface water are given for comparison.

pH	Cond. (µS/cm)	As (ppb)	Ba (ppb)	Co (ppb)	Cu (ppb)	Mn (ppb)	P (ppb)	Se (ppb)	Zn (ppb)	SO4 (mg/L)
Physical properties and concentrations of selected elements (Min.-Max. values) in surface water of the Kafue River, inflow to the industrial area of the Copperbelt.										
6.4–6.8	20–65	<0.5	14–15	<0.5	2–4	6–19	31–36	<0.5	1–2	<0.3–-1.9
Physical properties and concentration of selected elements (minimal-maximal values) at monitored sites of the Kafue River tributaries, Copperbelt (Min.-Max. values)										

5.8-7.43	95–330	<0.5–2.9	23–168	3–5824	5–29,400	6–2344	41–604	<2–25	1.5–503	36–1850
Physical properties and concentrations of selected elements (minimal-maximal values) at monitoring sites of the Kafue River, outflow from the Copperbelt Area										
	200-310	<0.5–0.8	42–33	19–33	39–66	140–170	60–64	<0.5–0.9	2.6–4.6	42–93
Zambian limits for effluents and waste water (after ECZ 2010)										
6.0-9.0	4300	50	500	1000	1500	1000	6000	20	10,000	1500
Czech and European Union standards for surface water										
		20	500	10	30	500	150	5	200	300

5 Conclusions

The results of the environmental-geochemical monitoring in the area of the Zambian Copperbelt can be summarized as follows:

1. Contamination of terrestrial systems (soils and vegetation) is mostly ascribed to dust fall-out from smelters, crushers, and dry beaches of tailing impoundments.

2. Concentrations of As, Co, Cu, Hg, Pb, Zn, S and Se in surface soils are usually higher when compared with subsurface soils. These elements reflect an extent of industrial contamination.

4. Contents of heavy metals in agricultural plants depend on anthropogenic contamination and bedrock geochemistry. Dietary exposure to metals and arsenic through the consumption of these vegetable crops has been identified as a low risk to human health. However, surfaces of leaves are strongly contaminated by metalliferous dust in the polluted areas. Compared with cassava and sweet potatoes, maize grains are less affected by industrial contamination.

3. Contamination of surface waters and stream sediments is ascribed to siltation that results from washout of fine particles from dumps and ore-processing plants, overflow from tailing facilities, leakage of water through the tailing facilities and the drainage of technological water from smelters and acid plants. High and extreme high contamination were detected in sediments of the Mushishima and Changa rivers (Chingola area), and in the Uchi and Wanshimba rivers (Kitwe area).

6. Extreme high concentration of dissolved Cu was found in waters of the Mushishima River, high concentration of Co was found in Mushishima, Changa and Uchi rivers. However, the environmental impact of mining and related activities on the Kafue River is relatively limited due to a high neutralizing capacity of the mining wastes which control the rapid precipitation of iron oxides and hydroxides as well as adsorption and/or co-precipitation of copper, and cobalt.

7. It was documented that the results obtained from the geochemical mapping of stream sediments, soils and vegetation can be used to characterize the extent of contamination even in areas with multiple geological and anthropogenic sources of heavy metals.

It is believed that results of this investigation can be used by government administrative units to accentuate their efforts in coordinating environmental management, promotion of public awareness and minimization of environmental deterioration in areas affected by mining and processing of raw materials. Local administrative authorities such as city and municipal councils on the Copperbelt can use the results as a foundation for an improved decision-making at all levels beginning with allocation of land-use zones in town planning to the sustainable development in the use of raw materials. Based on the results of this research, more efficient environmental impact assessment and reclamation of tailing impoundments and waste deposits can be carried out by various agencies, enabling them to immediately deal with the most critical issues of land and environmental management. To assess the impacts of mining and processing of ore, the cooperation with medical staff is highly desirable in the Copperbelt area to evaluate the impacts of ore mining and processing to human health.

Acknowledgements

The study originated within the Project of the Development Cooperation between the Czech Republic and Republic of Zambia. Interpretation of results was carried on within the IGCP/SIDA Project 594 “Assessment of impacts of ore mining and mineral processing on the environment and human health in Africa”. The authors are grateful to P. Bezusko, J. Godanyi, V. Pecina, and P. Rambousek (Czech Geological Survey), F. Chibesakunda, M. Mwale, K. Mwamba, A. Dokowe (Geological Survey Department, Ministry of Mines and Mineral Development, Zambia) and S. Simasiku (University of Zambia, School of Mines, Geology Department) for their participation and initiative in field operations and in the interpretation of the interim results produced during the years 2002–2010.

References

Ashey, PM, Lottermoser BG, Collins AJ, Grant, CD (2004) Environmental geochemistry of Webbs Consols mine, New South Wales, Australia. Environmental Geology 46, 591–604.

Barcan, V, Kovnatsky, E (1998) Soil surface geochemical anomaly around the copper-nickel metallurgical smelter. Water Air & Soil Pollution 103, 197–218.

CCME (Canadian Council of Ministry of the Environment) (2000) Protocol for the derivation of Canadian sediment quality guidelines for the protection of aquatic life. CCME-EPC-98E. Prepared by the Environment Canada, Guidelines Divission, technical secretariat of CCME, Toronto.

Chukwuma, ChSr. (1995) Evaluating baseline data for copper, manganese, nickel and zinc in rice, yam, cassava and guinea grass from cultivated soils in Nigeria. Agriculture, Ecosystems and Environment 53, 47-61.

Davis, A, Ruby, MV, Bergstrom, PD (1992) Bioavailability of arsenic and lead in soils from the Butte, Montana. Environmental Science & Technology 27, 1415–1425.

Davis, A, Ruby, MV, Bloom, M, Schoof, R, Freeman, G, Bergstom, PD (1996) Mineralogic constraints on the bioavailability of arsenic in smelter-impacted soils. Environmental Science & Technology 30, 392–399.

Dudka, S, Adriano, DC (1997) Environmental impacts of metal ore mining and processing: A review. Journal of Environmental Quality 26, 590–602.

ECZ (2010) Minimum specification for health care waste incineration in accordance with the Environmental Protection and Pollution Control Act (Amendement) No. 125 of 2001, the Hazardous Waste Management Regulations Statutary Instrument No. 125 of 2001. Environmental Council of Zambia, Lusaka.

FAO-UNESCO (1997) Soil map of the world 1:500 000. Volume VI. Africa: UNESCO, Paris.

Goodarzi, F, Sanchi, H, Garrett, R, Duncan, W (2002) Accumulation of trace metals on the surface soils around the Trail Smelter, British Columbia, Canada. Environmental Geology 43, 29–38.

JECFA – Joint FAO/WHO Expert Committee on Food (2007) database of food additives and pollutants.- httm://jecfa.ilsi.org/search.cfm, visited 10-02-2007.

Kachenko, AG, Singh, B (2006) Heavy metals contamination in vegetables grown in urban and metal smelter contaminated sites in Australia. Water, Air, and Soil Pollution 169, 101–123.

Kamona, AF, Nyambe, IA (2002) Geological characteristics and genesis of stratiform sediment-hosted Cu-(Co) deposits, Zambian Copperbelt. In: Miller R. E. (ed) Proc. 11th IAGOD Quadrennial Symposium and Geocongress, Extended Abstracts. Geological Survey of Namibia, Windhoek Namibia (CD version).

Křibek, B, Majer, V, Nyambe, IA (2007) Environmental-geochemical atlas of the Central-northern part of the Copperbelt Province of Zambia. Czech Geological Survey, Prague.

Křibek, B, Majer, V, Veselovský, F, Nyambe, IA (2010) Discrimination of lithogenic and anthropogenic sources of metals and sulphur in soils of the central-northern part of the Zambian Copperbelt Mining Districs: A topsoil vs. subsurface soil concept. Journal of Geochemical Exploration 104, 69–-86.

Li X, Thornton, I (2001) Chemical partitioning of trace and major elements in soils contaminated by mining and smelting activities. Applied Geochemistry 16, 1693–1706.

Oomen, A.G., Hack, A., Minekus, M., Zeijdner, E., Cornelis, C., Verstaete, W., Van de Wiele, T., Wragg, J., Rompelberg, CJM., Sips, AJ, van Wijnen, JH. (2002) Comparison of five in vitro digestion models to study the bioaccessibility of soil contaminants. Environmental Science and Technology 36, 3326-3334.

Reimann, C, de Caritat, P (1998) Chemical elements in the environment-factsheets for the geochemist and environmental scientist: Berlin, Germany, Springer-Verlag.

Reimann, C, Garrett, G (2005) Geochemical background-concept and reality. Science of the Total Environment 350, 12–27.

Salminen, R, Tarvainen, T, Demetriades, A, et al. (1998) FORGES geochemical mapping field manual. Geological Survey of Finland, Guide 47. Geological Survey of Finland, Espoo.

US EPA (2007) Estimation of relative bioavailability of lead in soil and soil-like materials using in vivo and in vitro methods. Office of Solid Waste and Emergency Response, US EPA, Washington, OSWER 9285.7-77.

ZCCM – Zambia Copper and Cobalt Mining Investment Holding (2002) Environmental assessment of the Copperbelt and Kabwe areas. MS E539, ZCCM IH, Plc., Kitwe, Zambia.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

The heavy minerals in the Kafue River sediments, the Copperbelt Mining District, Zambia: Indicators of industrial contamination

Bohdan Kříbek, František Veselovský, Jan Malec, Ilja Knésl & Vladimír Majer
Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic, e-mail: bohdan.kribek@geology.cz

Martin Mihaljevič & Vojtěch Ettler
Institute of Geochemistry, Mineralogy and Mineral Resources, Faculty of Science,
Charles University in Prague, Czech Republic

Ondra Sracek
Department of Geology, Faculty of Science, Palacký University in Olomouc, Czech Republic

Imasiku Nyambe,
University of Zambia, School of Mines, Department of Geology, P O Box 32379, Lusaka, Zambia, e-mail: inyambe@unza.zm

Abstract. The identification of heavy minerals and their relative proportions enabled to assess the extent of contamination of stream sediments and also the character of individual sources of contamination. No extensive dissolution of copper and cobalt minerals in stream sediments takes place due to the neutral or slightly alkaline character of surface waters in the area. However, occasional accidents in chemical plants processing copper and cobalt ores result in short-term but sharp increase in acidification of surface waters which consequently leads to the dissolution of heavy minerals and to sharp increase in copper contents in these waters. These "acid spikes" disturb for long time the stability of aquatic ecosystems in the Kafue River and in its contaminated tributaries.

Keywords: Kafue River, heavy minerals, industrial contamination, Copperbelt, Zambia

1 Introduction

Mining and processing of copper and cobalt ores in the Zambian sector of the Copperbelt are reflected in contamination of surface waters and stream sediments of the Kafue River that drains the whole of the Copperbelt Region (Fig. 1). Because of a great fluctuation of the Kafue River and its tributaries flow rate, the data on water quality characterize actual state of the contamination in a limited time-span. Therefore, long-term trends in contamination of the Kafue River catchment contamination was assessed using stream sediment sampling (Sracek et al., 2011). This contribution summarizes new data on the distribution and speciation of Cu, Co and other elements in the Kafue River sediments. Particular attention was paid to the distribution of heavy minerals in sediments as indicators of the extent and sources of contamination.

2 Methods

The pseudo-total digests of stream sediment samples were obtained by a standardized *aqua regia* extraction protocol in accordance with the ISO 11466 procedure (International Organization for Standardization 1995). Sequential extractions for selected bulk sediment samples were performed using the BCR procedure (Rauret et al., 1999). Heavy fraction of sediments was examined under a Leica DM LP polarizing microscope and representative microphotographs were taken using an Olympus Camedia C-5050 ZOOM digital camera. Determination of the mineralogical identity of heavy minerals in stream sediments was attempted using a CamScan 3200 electron microprobe in SEM mode equipped with an energy-dispersive analyzer LINK-ISIS. Analyses were undertaken using an accelerating voltage of 20 kV, and a beam current of 3.10-9 A.

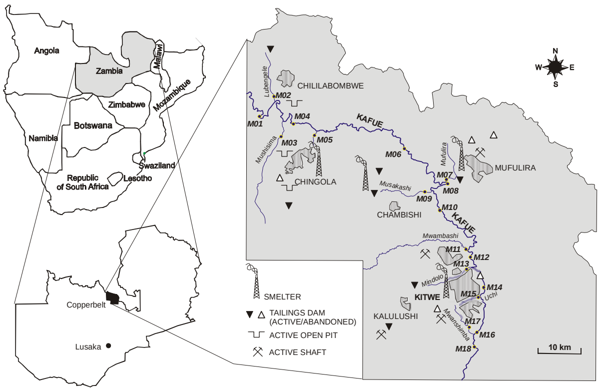

Figure 1. Location of Zambia, the Copperbelt Mining District, main sources of contamination and location of sampling sites at the Kafue River and its tributaries.

3 Results

3.1 Composition of sediments

Contaminated sediments of the Kafue River were found to contain up to 0.8 wt.% Cu, 0.1 wt.% Co, 0.3 wt.% Mn and increased amounts of Pb, As and Hg compared with uncontaminated Kafue sediments (Tab. 1).

The results of sequential extraction revealed that the substantial amount of Cu, Co and Mn in contaminated sediments are bound to the acid extactable fraction (exchangeable metals and carbonates), whereas the majority of metals in uncontaminated sediments of Kafue are confined to oxidizable (organic matter) and residual fractions.

In contaminated Kafue sediments, oxidizable fraction is represented mostly by sulphides (pyrite, chalcopyrite).

Table 1. Contents of some chemical elements in uncontaminated and contaminated sediments of the Kafue River and its tributaries

Element (ppm)	Co	Cu	Pb	As	Hg	Mn
Uncontaminated Kafue	17-21	115-161	4-13	0.14-0.57	0.02-0,03	103-133
Contaminated Kafue	131-1174	1520-8837	21-54	1.9-7,4	0.03-0,14	395-2849

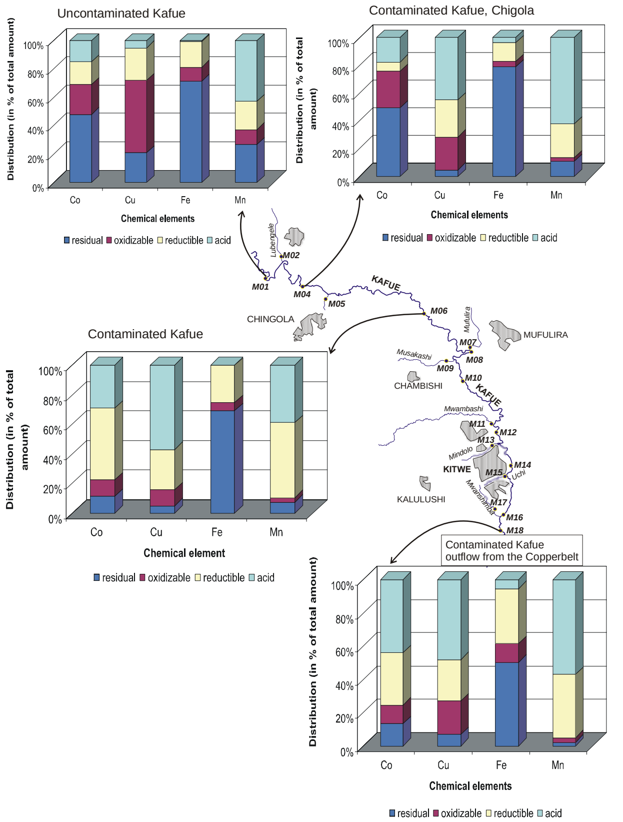

Figure 2. Results of sequential extractions show that compared with uncontaminated sediments, substantially higher amount of Cu, Co and Mn are bound to the acid-extractable fraction (exchangeable metals and carbonates).

3.2 Heavy minerals

Heavy minerals found in uncontaminated as well as in contaminated sediments of the Kafue River consist mostly of ilmenite, limonite, rutile, amphibole and tourmaline, while apatite, clinochlore, and zircon are minor (Table 2). On the other hand, the contaminated sediments contain, besides rock-forming minerals, chalcopyrite, pyrite, bornite, malachite and azurite the concentrations of which vary considerably. Limonite with elevated content of Cu is characteristic component of contaminated sediments. Contents of sulphides and carbonates of copper increase with decreasing distance from single sources of contamination. In addition to sulphides and carbonates, particles of slag rich in magnetite and particles of intermediate solid solution (ISS) of Cu-Co-Fe-S(-O) were found in the Kafue River sediments (Fig. 3).

Table 2. Minerals identified in heavy fraction of uncontaminated and contaminated sediments of the Kafue River

Uncontaminated Kafue River	Contaminated Kafue River
Ilmenite, hematite, hornblende, clinochlorite, rutile, zircon, dravite, apatipe, albite, microcline	Hematite, **chalcopyrite, pyrite, goethite, bornite, covellite, malachite, pseudomalachite, azurite, native copper, spioncopite**, hornblende, muscovite, chlorite, clinozoisite, rutile, zircon, dravite, quartz, albite

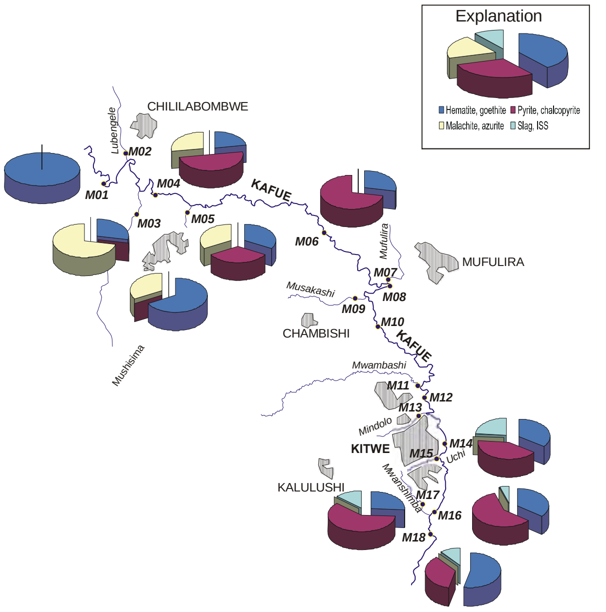

Figure 3. Distribution of hematite, goethite, pyrite, chalcopyrite, malachite, azurite, slag and intermediate solid solution Cu-Co-Fe-S(-O) (ISS) particles in the Kafue River sediments (in %).

4 Discussion

In the Kafue River sediments, chalcopyrite and pyrite evidently come from leaks of tailings ponds still in operation in which the sulfides were not yet oxidized. Reprocessing (re-washing) of old slimes in Chingola for chemical leaching, and erosion of old flotation tailing ponds are responsible for enhanced contents of malachite, azurite, bornite, copper metal and chrysocolla together with limonite with high contents of copper and other elements in the Kafue River sediments (Fig. 6 A,B). Particles of slag rich in magnetite and also particles of intermediate solid solution of Cu-Fe-S (ISS) were found in sediments close to the smelters (Fig. 6 C,D).

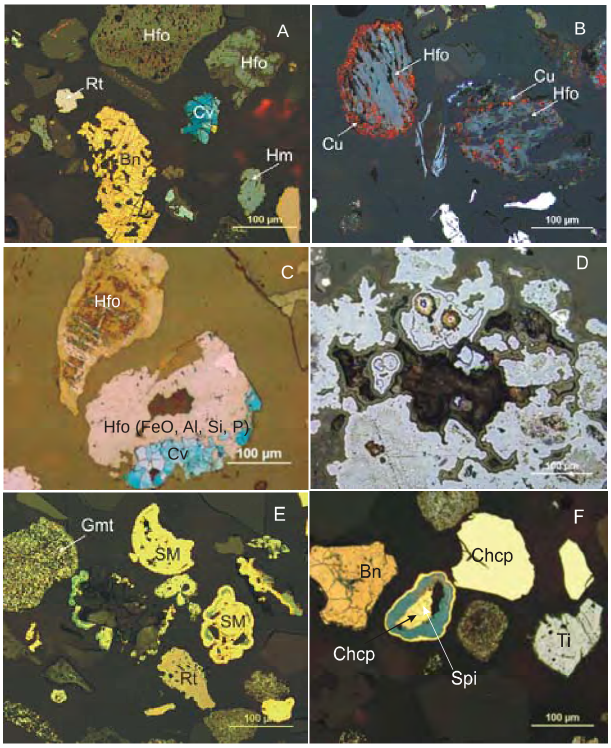

Figure 4. Microphotographs of heavy minerals in contaminated Kafue River sediments. A: Rutile (Rt), bornite (Bn), covellite (Cv), limonite/goethite (Hfo). Mushishima River, Chingola Area. B: Limonite/goethite (Hfo) with copper metal (Cu). Kafue River, downstream of the Chingola Town. C: Limonite/goethite, (Hfo), limonite/goethite with admixture of Al, Si and P and grain of covellite (Cv), Mushishima River, Chingola Area. D: Limonite/goethite. Mushishima River, Chingola Area. E: Magnetite-rich slag particle (Gmt), rutile (Rt) and intermediate solid solution (ISS) particle with oxidation rims (SM). The Uchi River, Kitwe Area. F: Bornite (Bn), chalcopyrite (Chcp), titanite (Ti) and chacopyrite with a rim of secondary spionkopite (Spi). The Uchi River, Kitwe Area.

5 Environmental consequences

Due to neutral or slightly alkaline character of the Kafue River water (Table 3) it can be assumed that no extensive dissolution of copper and cobalt minerals takes place in the Kafue River sediments. However, occasional accidents in chemical plants processing copper and cobalt ores result in short-term but sharp increase in acidification of surface waters of the Kafue River tributaries (pH = 3.62 Chambeshi River, pH = 2.04 Uchi River, Table 3) which consequently leads to sharp increase in copper and cobalt contents in these waters. These "acid spikes" disturb for long time the stability of aquatic ecosystems in the River Kafue and in its contaminated tributaries.

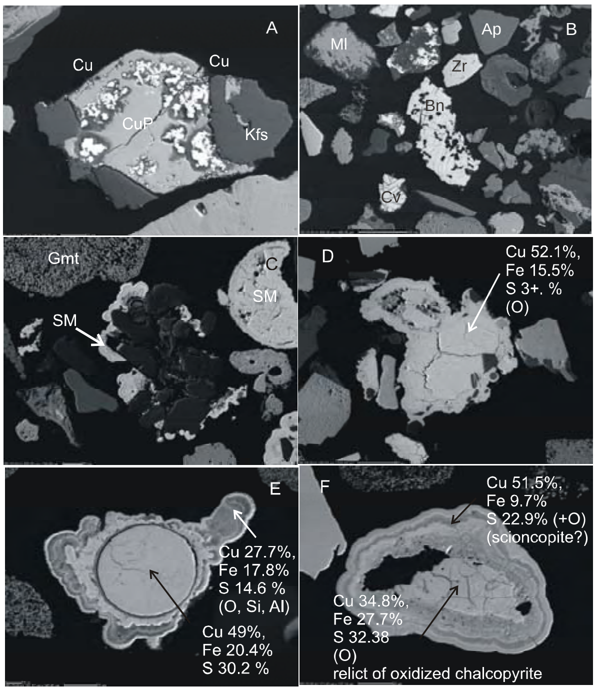

Figure 5. Components of contaminated sediments of the Kafue River and its tributaires. A: Cu-phosphate (Cu,P - pseudomalachite?) with accumulation of native copper (Cu) and grain of microcline (Kfs), Changa River. B: Bornite (Bn), malachite or azurite (? Mi), apatite (Ap) covellite (Cv) and zircon (Zr), Kafue River, Chingola area. C: Intermediate solid solution of Cu, Fe and S (SM) in sedimentes of the Uchi River (trubutary of the Kafue River in Kitwe). D-F. Chemical composition of different types of intermediate solid solution particles (Cu-Fe-S, Cu-Fe-Co-S and Cu-Fe-S-O) in sediments of the Uchi and Lwanbisha rivers, Kitwe area. SEM, backscattered electrons.

Table 3. The pH values and concentration of chemical elements in uncontaminated and contaminated Kawue River water. The pH values and concentration of metals in surface water during acid spikes in the Chambeshi and Uchi rivers (contaminated tributaries of Kafue) are given for comparison.

	Uncontaminated Kafue (206-2010)	Contaminated Kafue (2006-2010)	Acid spike Chambeshi July 7-10, 2006	Acid spike Uchi July 7-10, 2006
pH	6.8-7.1	6.9-7.2	3.62	2.04
Al (ppb)	4-8	11-21	6929	2115
As (ppb	<0.5	<0.5-2.9	6.5	872
Cd (ppb)	<0.05	<0.05-3.43	2.0	7:0
Co (ppb)	<0.05	10-30	29,528	909
Cu (ppb)	2.5-4.2	38-107	16,442	7683
Mn (ppb)	19-25	200-374	8673	466
Pb (ppb)	<0.2	0.2-0.7	317	161

Figure 6. Source of the contamination of the Kafue River sediments. A: Washing out (re-working) of old flotation tailings for chemical leaching, Chingola area. Due to an insufficient volume of the retention reservoir, suspension of tailings overflow the retention dam. B: Siltation of the Changa River (Chambishi Area) with outflow from waste heaps. C: Slag deposits at the Nkana (Kitwe) Smelter. D: Washout from slag deposit is one of the important sources of contamination of the Kafue River sediments.

Figure 7. Occasional accidents in chemical plants processing copper and cobalt ores result in short-term but sharp increase in acidification of surface water. During the “acid spikes”, copper minerals in sediments are dissolved and the concentration of copper in surface water substantially increases. As a consequence, chalcanthite ($CuSO_4.7H_2O$, blue colour) crystallize together with gypsum (white colour) on dry banks of the Uchi River (tributary of the Kafue River in Kitwe).

Acknowledgements

The study originated within the UNESCO/IGCP Project 594 “Assessment of impacts of ore mining and mineral processing on the environment and human health in Africa”.

References

Sracek, O., Kříbek, B., Mihaljevič, M., Majer, M., Veselovský, F., Vencelides, Z., Nyambe, I. (2011): Mining-related contamination of surface water and sediments of the Kafue River drainage system in the Copperbelt district, Zambia: An example of a high neutralization capacity system. Journal of Geochemical Exploration (submitted).

Rauret, G., López-Sanchez, J.F., Sahuquillo, A., Rubio, R., Favidson, C., Ure, A., Quevauviller, P. (1999): Improvement of the BCR three step sequential extraction procedure prior to the certification of new sediment and soil reference materials. J. Environ. Monit. 1, 57–61.

An Artisanal Mining Environmental Code of Practice for Namibia

Rosina Ndahafa Leonard
Ministry of Mines and Energy, Geological Survey of Namibia, 1 Aviation Road, P/Bag 13297, Windhoek, Namibia
kndalulilwa@mme.gov.na

Morgan Hauptfleisch
Southern African Institute of Environmental Assessment (SAIEA), PO Box 6322, Windhoek, Namibia

Rainer Ellmies
BGR-GSN Project, Geological Survey of Namibia, 1 Aviation Road, P/Bag 13297, Windhoek, Namibia

Abstract. Generally, artisanal or small-scale mining is conducted in an informal manner which is difficult to regulate. The cumulative impacts resulting from this type of mining can have severe biophysical and social consequences. In some regions in Namibia, the Ministry of Mines and Energy with the National Planning Commission have established a programme to facilitate regulation of this industry. The programme analysed the baseline situation of artisanal mining in terms of its economics, social and environmental consequences. Following a situation analysis, an Environmental Code of Practice (ECOP) was developed to maximise economic and social benefits to local communities, and minimise environmental damage. The ECOP was developed in consultation with artisanal miners of the regions and contains pragmatic and affordable mitigation measures. These measures are separated into five main categories illustrated within the ECOP as a “green hand” of responsible small mining: i) co-operate with landowners; ii) mine "light” and rehabilitate; iii) work safely; iv) locate camps cleverly; and v) manage waste. Adherence to the ECOP is not yet a legal requirement; however miners are encouraged to implement it as it provides a number of incentives; which includes a more saleable product, mined with less environmental harm; and better relationships with landowners where minerals are mined.

Keywords. Artisan or small-scale miners, Environment, Environmental Code of Practice, Namibia

1 Introduction

The Ministry of Mines and Energy (MME) estimates that about eighty percent of the estimated 1000-10000 small-scale miners are not legal. While it is recognized that small-scale mining creates opportunities for employment and encourages entrepreneurship, the lack of monitoring of small-scale mining activities can lead to labour malpractices and environmental degradation. These impacts can negatively affect natural resources as well as create a negative perception of the product and brand of gemstone and crystal mining in Namibia.

The objective of the Environmental Situation Analysis is to describe, identify and assess the likely significant effects of small-scale mining on the Namibian biophysical and social environment. The report describes the cumulative impact of these effects and recommends mitigations for these impacts in the form of a practical environmental management plan (EMP). An environmental code of practice was introduced which should be adopted by small-scale miners.

2 Methods

A field inspection to the most important small-scale mining areas as well as the cutting and polishing factory in Karibib and the gemstone markets in Uis and Spitzkoppe junction, was undertaken in January 2010.

The inspection included:

- an estimate of the intensity of small-scale mining in different areas
- the extent of associated infrastructure
- the sensitivity of the ecosystems
- social setting in which small-scale mining takes place;
- The identification of biophysical and social impacts.

In addition, extensive public consultation was also done including:

- interviews with key stakeholders, including small-scale miners (legal and illegal), landowners, conservancy managers, traditional authorities, regional authorities, donor organizations, conservation organizations, minerals dealers and collectors and tourism operators
- Newspaper articles and radio interviews.

Relevant policies, laws and institutions pertaining to small-scale mining in Namibia were also considered.

3 Small-scale mining situations

3.1 Forces and dynamic

Most of the small-scale mining activities are mainly concentrated within the central Namib in cretaceous anorogenic rocks that contain a number of economically sought after accessory minerals such as topaz, quartz, tourmaline, aqua-marine, beryl, fluorite and apatite. Other products include dimension stones and building materials from the northwest and the southern part of Namibia.

Figure 1 is a schematic representation of the forces and dynamics of the small-scale mining.

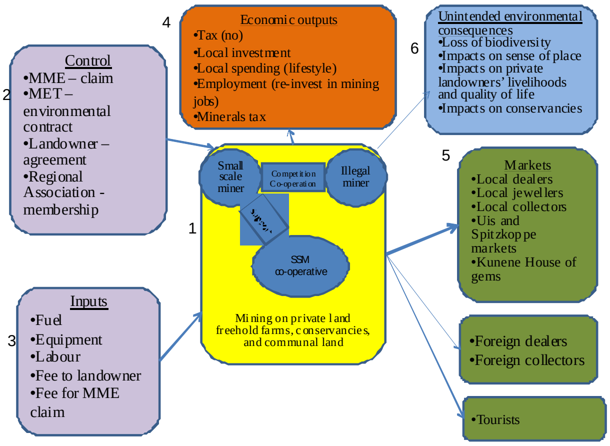

Figure 1. Forces and dynamics of small-scale mining.

4 Regulatory frameworks

The Minerals (Prospecting and Mining) Act 33 of 1992 is the main legal mechanism controlling the allocation of mineral rights in Namibia. In order to undertake mineral prospecting and mining operations, small scale miners SSMs must adhere to an environmental contract, issued by Ministry of Environment and Tourism (MET) in consultation with MME. Additionally, SSM also had to adhere to the Communal Land Reform Act 5 of 2002, The Soil Conservation Act No 76 of 1969 and the Soil Conservation Amendment Act No 38 of 1971, The Nature Conservation Ordinance 4 of 1975, Water Act 54 of 1956 and the National Heritage Act 27 of 2004.

The legislation dealing with environmental issues in terms of small-scale mining remains fragmented and sector based, despite the emergence of the Environmental Management Act, which has not yet been properly implemented. Other legislation that can have an impact on the small-scale mining sector includes the proposed Parks and Wildlife Management Bill and the Water Resources Management Act of 2004 – both of which are not yet implemented. Furthermore, land use planning is characterised by conflicting policies between various ministries and devolution of authority is easily overridden by centrally placed government agencies. The ultimate decision making lies in the Ministry at a central level. It is also clear that established guidelines have been set in order to organise and promote the small-scale mining sector, and it appears that the process is working to the extent that small-scale miners are being drawn into the formal economy via co-operations and organised associations. This in turns bodes well for co-ordinated approach to management and capacity building of this important economic sector. There is however, room for improvement in this regard. There appears to be inadequate capacity within the Ministries to properly monitor this sector insofar as training and technical assistance is required.

In spite of the existing safeguards noted earlier, there remain environmental concerns because of factors such as:

- The large number of miners (legal or illegal) involved in this sector.
- The fragile environments where mining activities occur.
- The weak incentives and disincentives for compliance with permit conditions and best practice guidelines.

However, care should be taken to balance the requirements of law and administrative concerns with the needs of the small-scale mining fraternity and their socio-economic role. Small-scale mining organisations need environmental, technical and economic support in order to promote a self-policing industry that will root out informal and illegal operators.

5 Results

An Environmental Code of Practice (ECOP) is proposed to guide small-scale mining operations in order to minimise the impacts identified regionally (Fig 2). The code of practice is a visually explanatory document based on five key points of practice which, when implemented correctly, will address all of the identified impacts. The key points are described in Table 1.

Table 1. ECOP points and the impacts they address

ECOP point	Impacts reduced
Co-operation with landowners	• Poaching • Litter & waste • Risk of fire • Security risk • Disruption of farming activities • Interference with tourism
Mine “light” and rehabilitate	• Visual • Erosion • Interference with tourism • Risk to health & safety of miners
Work safely	• Risk of fire • Risk to health & safety of miners
Locate camps cleverly	• Wildlife displacement • Visual • Risk of fire • Risk to health & safety of miners • Damage to archaeological heritage
Waste management	• Litter & waste • Visual • Risk of fire

A commitment to implement the ECOP should be a precondition for the registration of claims and for membership in regional association. Figure 3 illustrates the institutionalisation of the ECOP.

When a small-scale miner applies for a mining claim, part of the application process includes an environmental screening questionnaire, and the signing of an environmental contract with MET. A commitment to the ECOP needs to be included in the environmental contract. The letter which is written to landowners informing them of the claim registration will be accompanied by the ECOP. This will allow landowners to monitor the implementation of the ECOP.

MET (Environmental commissioner under the EMA (2007)) should be responsible for monitoring compliance with the ECOP. The small-scale miner (as prescribed in the ECOP) will report on various aspects of the ECOP to association, and compliance must be reported by MET and landowners. Penalties for non- compliance will be decided on by MME, and action will be taken accordingly, either cancelling claims or black-listing miners for future claim applications.

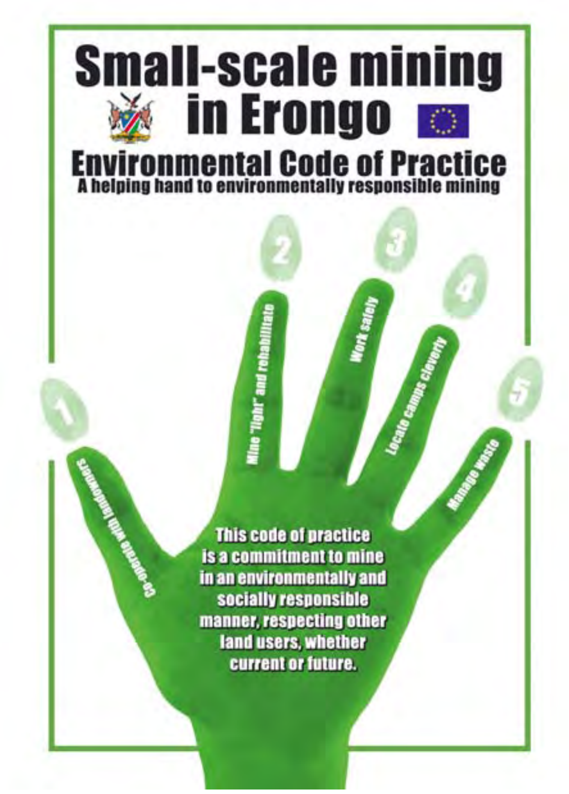

Figure 2. Code of Practice for Small-scale mining

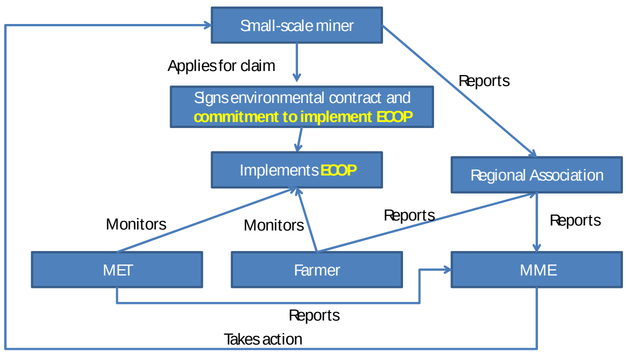

Figure 3. Implementation of the Environmental Code of Practice (ECOP).

6 Conclusions

Small-scale mining in the Erongo region has the potential to be a reasonably sustainable livelihood strategy. Although it currently exists with minimal conflict with other land-uses, it can be operated in harmony with other land-uses towards a synergistic relationship with other valuable industries, such as tourism. Mining intensity varies from heavy to moderate and light, hence its success also varies.

Numerous impacts on the socio-economic and biophysical impacts of small-scale mining were identified. Impacts of high significance are:

- Security risk to landowners;
- Poaching (in a socio-economic sense);
- Disruption of day-to-day activities; and
- Damage to archaeological heritage.

Impacts of medium significance are:

- Wildlife displacement;
- Visual scarring;
- Risk of fire;
- Erosion;
- The biophysical impact of poaching;
- Interference with tourism; and
- Safety of miners.

A number of positive impacts were also identified, including the provision of jobs for locals and stimulus of local economy.

For each negative impact, mitigation actions are recommended. With implementation of these mitigations all negative impacts can be reduced to low significance. Enhancements of positive impacts are also proposed. An environmental management plan is proposed which details the implementation of these mitigations.

7 Acknowledgements

The following institutions are acknowledged for being instrumental in the initiation and completion of this project:

The National Planning Commission (NPC) - Rural Poverty Reduction Programme (RPRP) and (EU) for financially supporting this project. The BGR-GSN Project of Technical Co-operation for technical guidance and assistance with the fact-finding field trip. The Erongo Regional Council for allowing discussions at their stakeholder forum, Erongo Reginal Small-Scale Miners Association (ERSMA) and Kunene Regional Small-Scale Miners Association (KUNSMA) for co-operations and provision of information, numerous small mining co-operatives and small scale miners, jewellers, landowners and traditional authorities.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Soil contamination and health risks associated with former Pb and Zn ore smelting in Kabwe, Zambia

Vladimír Majer, Ilja Knésl & Bohdan Křibek
Czech Geological Survey, Geologická 6, 152 00 Prague 5, Czech Republic (bohdan.kribek@geology.cz)

Imasiku A. Nyambe & Gabriel Ziwa
University of Zambia, School of Mines, Department of Geology, P O Box 32379, Lusaka, Zambia, e-mail: (inyambe@unza.zm)

Martin Mihaljevič & Vojtěch Ettler
Institute of Geochemistry, Mineralogy and Mineral Resources, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic (ettler@natur.cuni.cz)

Ondra Sracek
Protection of Groundwater Ltd., Bělohorská 31, 169 00 Prague 6, Czech Republic (srondra@yahoo.com)

Abstract. In order to distinguish natural concentrations of metals from those ascribed to contamination by dust fallout, the soil sampling in the area of former Pb and Zn smelter in Kabwe, Zambia, was undertaken at two depth horizons: in contaminated topsoil and in reference soil horizon at a depth of 80-90 cm which is not affected by dust fallout. It was found that total Cd, Pb, Zn, Cu and Se contents are significantly higher in topsoil relative to subsurface soil over a large part of the surveyed area. Contents of lead in the topsoil are as high as 4%, those of zinc reach maximum of 6.7%, copper 0.7%, arsenic 0.06% and selenium 0.01%. A modelling of gastric availability of lead and other metals revealed that the amount of available metals in topsoil increases in the following order: Fe, As, Cu, Mn, Co, Zn, Pb, Cd. This indicates that lead and cadmium pose the greatest environmental hazard when dust particles are swallowed as a result of eating unwashed vegetables or fruits. The amounts of metals in soils available for metabolism by plants (plant-available metals) increase in the following sequence: Fe, As, Co, Mn, Cu, Zn, Pb and Cd. Based on the results obtained from investigations carried out during the project, the contaminated area has been sub-divided into four zones each of which require specific measures that should be adopted in order to reduce health risks.

Keywords. Smelters, soil contamination, heavy metals, Kabwe, Zambia

1 Introduction

The environmental geochemical mapping of soils was carried out in the Kabwe Area, Central Province of Zambia. Strong contamination of soils as a result of smelting and roasting of base metal ores during the years 1904–1994 is the major problem faced by the inhabitants of the Kabwe area (ZCCM-IH 2002, Tembo et al., 2006). High concentrations of lead in soils, consumption of contaminated vegetables and inhalation of dust rich in lead result in high contents of lead in the blood of citizens living in the most affected compounds of town city of Kabwe. In 1994, altogether 866 people living in the compounds of Kasanda, Chowa, Mukebeko and Lukanda were tested for the content of lead in their blood (Hertzman 1995). The results of blood testing showed that mean lead concentration of lead in the blood of inhabitants of the Kasanda, Chowa and Mukobeko and Lukanga compounds highly exceed the maximum World health organization (WHO) permissible value for lead concentration in human blood (10 μg/L). The main objectives of the current investigation were to: (1) delimitate the extent of soil contamination and compare the intensity of contamination with Canadian environmental guideline values for agricultural, residential, commercial and industrial land-use, (2) determine gastric availability of metals in the topsoil and the amount of plant-available metals in soils and, (4) to propose measures to reduce anthropogenic contamination and health risks in the Kabwe area.

2 Materials and Methods

Regional environmental geochemical mapping of soils, stream sediments and vegetation at the Kabwe area was carried out using the methodology recommended for the regional geochemical mapping by the FOREGS Geochemistry Working Group (Salminen et al., 1998). At selected sampling sites, composite samples of the lower soil horizon were taken from a depth of 70 to 90 cm using a soil probe. The size fraction of < 2 mm was homogenized in an agate ball mill and was used for chemical analyses. For the determination of plant-available metals, samples were extracted with solution of diethylentriaminepentanacetic acid (DTPA) and trethanolamine (TEA) according to the ISO/DIS 14870 method. To simulate gastric availability of metals in human stomach in course of dust swelling, the fine fraction of contaminated and uncontaminated surface soil (top-soil) samples were extracted with the glycine and HCl solution (Davis et al., 1996). Trace elements in all types of material were determined in the Central Analytical Laboratory of the Czech Geological Survey following accredited methodology. Fe, Cd, Cu Mn, Pb and Zn were analyzed using flame atomic absorption spectroscopy (FAAS). Analyses were performed on the PE 4000 spectrometer. Arsenic was determined by a hydrite-generation atomic absorption spectrometry (HGAAS) using a PE 503 equipment.

3 Results and Discussion

3.1 Assessment of contamination of soils on a regional scale

Areal distribution of Pb, As, Cu and Se in the area surveyed is shown in Figure 1. Individual maps depict data on concentration of variables in topsoil and in the subsurface soil horizon. Concentrations of single elements in topsoil (at a depth of 0–3 cm) are expressed in contours and sampling points are marked by black dots. Samples from subsurface soil horizon are depicted by points and contents of metals within single points are distinguished by different colours. This graphic presentation enables to correlate content of the given element in topsoil with concentration of the same element in deeper soil horizon. It is established that contents of lead in the topsoil are as high as 4%, those of zinc reach a maximum of 6.7%, copper 0.7%, arsenic 0.06% and selenium 0.01%. The highest concentrations of metals in soils are confined to the industrial zone in the immediate environs of the former smelter, but soils in the Kasanda and Railway residential areas were also found to be highly contaminated. Strongly contaminated soils were also identified in some parts of the Chowa and Katondo compounds and in large areas of downtown Kabwe. Maps with various colour hachures indicate areas where contents of certain elements in topsoil exceed a maximum of the Canadian soil quality guidelines for metals with regard to the land-use of these soils. As these permissible values of soil contamination do not exist either in Zambia or in any sub-Saharan country, the Canadian environmental guideline values for metals, that we consider to be the best and most carefully formulated and defined, were used in our investigations. Maximum permissible ecological limits used in Canada with regard to various land-use are given in Table 1. Providing the quality guidelines do not differ for various land-uses the same hachure is used in individual maps. Using the Canadian criteria, the surveyed region was classified into areas unsuitable for farming, those unsuitable for housing development and those unsuitable for commercial and industrial activities.

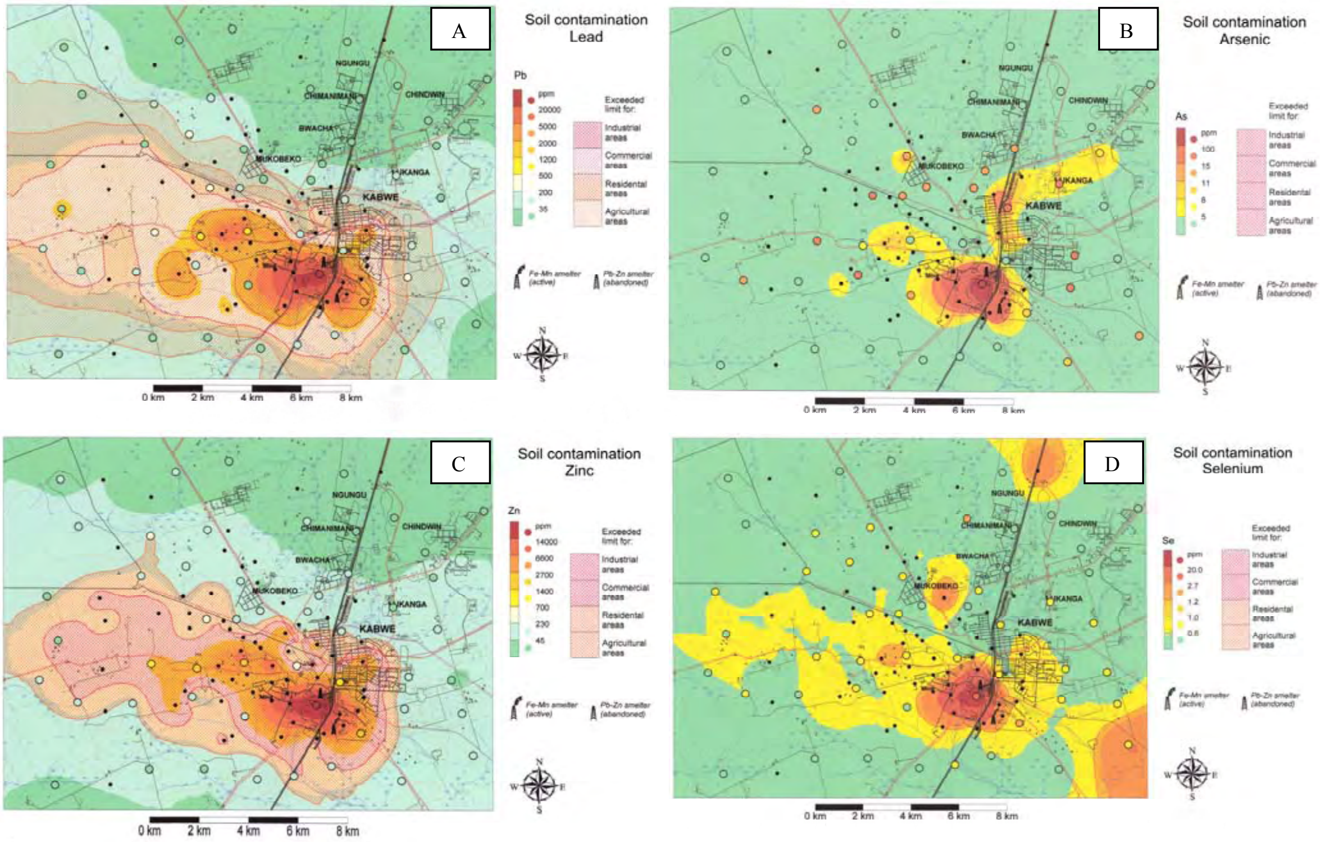

Figure 1. Contour map of some elements in topsoil and classed points map of contents of the same elements in deeper soil horizon in the Kabwe area, Zambia. Sampling sites of topsoil are marked by black dots. Areas exceeding Canadian environmental thresholds for different land-use are depicted using colour hatchures. A: Lead, B: Arsenic, C: Zinc, D: Selenium.

Table 1. Soil quality guideline values for metals for agricultural, residential, commercial and industrial land uses in Canada (CCME, 2007). Concentrations in ppm.

Land use/ Chemical element	Agricultural Land use	Residential Land use	Commercial Land use	Industrial Land use
Cr	64	64	87	87
Ni	50	50	50	50
Cu	63	63	91	91
Zn	200	200	360	360
Ba	750	500	2000	2 000
Pb	70	140	260	600
As	12	12	12	12
Se	1	1	2,9	2.9

3.2 Determination of gastric availability of metals in dust to the human gastric system and for metabolism of plants

A test modelling the intake of lead and other metals through swallowing of dust particles or by ingestion of dust through consumption of unwashed vegetables or fruit was used to assess the gastric availability of metals. The amount of metal released during this test increases in the following order: Fe → As → Cu → Mn → Co → Zn → Pb → Cd. This indicates that lead and cadmium pose the greatest environmental hazard when dust particles are swallowed as a result of eating unwashed vegetables or fruits. The amounts of metals in soils available for metabolism by plants (plant-available metals) were established by extraction into chelatone solution (DTPA). The tests undertaken showed that the amounts of bio-available metals increase in the following sequence: Fe → As → Co → Mn → Cu → Zn → Pb → Cd. Because lead and cadmium in soils occur in very bioavailable form, this result is very unfavourable for agriculture. Therefore, the experiments were undertaken to reduce bioavailability of lead and cadmium for plant metabolism. Results of the experiments indicate that the amount of plant bioavailable cadmium and lead substantially decreases in phosphate-treated samples. The addition of phosphate does not affect the amount of bioavailable zinc (Fig. 2).

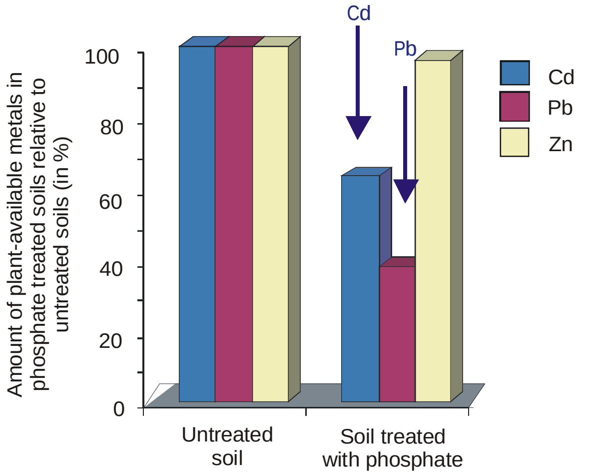

Figure 2. The average amount of plant bioavailable cadmium, lead and zinc in untreated and in phosphate-treated topsoil from the Kabwe area, Zambia. Amount of bioavailable Cd, Pb and Zn in untreated samples = 100%.

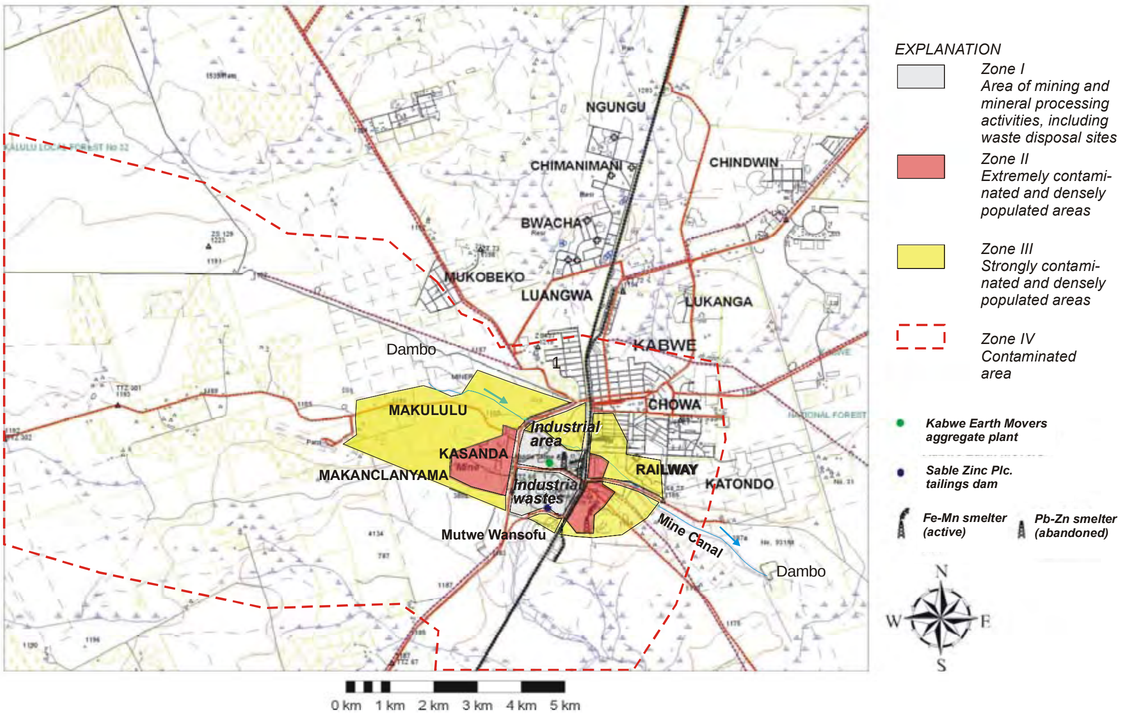

Figure 3. Sub-division of the town of Kabwe and its environs into separate zones based on the degree of metal contamination of the soils. Measures recommended to minimize the impact of contamination on human health in each of these zones are specified in the text.

3.3 Measures proposed to reduce anthropogenic contamination and health risks in the Kabwe area

Based on the results obtained from investigations carried out during the project, the contaminated area has been sub-divided into four zones (Fig. 3), each of which require specific measures that should be adopted in order to reduce health risks.

Zone I comprises the areas of mining and mineral processing activities, including waste disposal sites. This zone is mostly contaminated by dust fallout. The whole area should be fenced off in order to prevent trespassing by people. As part of a long-term remedial programme, the slag settling ponds should be covered with soil and the grounds of the former smelter and ore dressing complex should be completely levelled. This will involve the demolition of ruined buildings and the removal of contaminated soils.

Zone II comprises extremely contaminated and densely populated areas i. e., part of Kasanda Compound adjacent to the highway connecting Lusaka with Kabwe, part of the Makululu Compound and the densely inhabited Railway Compound adjacent to the grounds of the former smelter.

The following measures are recommended for this zone:

◆ Reduce to a minimum the production of vegetables on soils in this area.

◆ Special attention to be paid during reclamation works to playing fields, particularly playgrounds and sports grounds adjacent to schools. Rehabilitation of these areas should be treated as a priority. Irrigation systems should be constructed and the areas covered with uncontaminated soil and grassed.

◆ The surfaces of unpaved and dusty roads should be treated because traffic on these roads is a source of dust fallout. Costly remedial works (asphalting, paving) can be restricted to the main access roads. The roads inside residential areas can be simply modified by rolling and wetting of imported laterite blended with a small amount of cement. Spraying of public areas and roads during the dry season would contribute significantly to reduction of dust. Addition of calcium chloride to the wetting solutions should be considered because it is a strongly hygroscopic substance which will cause aggregation of dust particles and prevent them from being dispersed by turbulence.

◆ The majority of houses in *Zone II* have no concrete floors but only loose or packed contaminated soil. The use of cheap mats made of leaves or straw would help to reduce contact with contaminated ground.

◆ Reduction of dust fallout can be achieved by planting trees. The following species are most suitable for this purpose: *Eucalyptus hybrid, Toona ciliata (Cedrella), Achrocarpus frazinifolia* and Acacia spp.

Zone III comprises strongly contaminated areas of the Makululu, Makanclanyama, Kasanda, Mutwe Wansofu, Chowa and Railway compounds of Kabwe Town. However, contamination by lead in these areas is lower than in *zones I and II*. In addition to the measures proposed for *Zone II*, the following are suggested for *Zone III*:

◆ On plots of land to be used for cultivation of vegetables, contaminated soil should be removed to a minimum depth of 30 cm. The prepared vegetable patches should be covered with permeable geotextile to prevent mixing of contaminated and uncontaminated soil. These vegetable patches should be filled with uncontaminated soil, the best source being the extensive marshes (dambo) occurring north of Kabwe Town. The space between vegetable patches should be sprinkled with plant waste (crushed cobs and stalks from maize field, crushed bark etc.). A more sophisticated method of reclamation in gardens (paving, asphalting) is not realistic because of the cost involved.

◆ Liming to increase the pH and stabilise of metals in soils or spraying with superphosphate solution (stabilization of adsorbed elements in soils) are recommended in the case of periodically cultivated farmland.

Zone IV comprises the contaminated central part of Kabwe Town and parts of a large area with scattered settlements (small farms) outside the town including part of the Mukobeko and Katondo compounds. Frequent spraying of streets and public areas of Kabwe Town is recommended, mainly during the dry seasons. Cheap methods of reclamation such as liming or use of phosphates are suggested for application on farmland outside Kabwe Town. Cultivation of maize that is resistant to contamination and non-food crops like cotton are recommended for farmlands away from the town.

4. Conclusions

Results of this study may be use in the implementation of systematic control measures to be undertaken in environmental protection in an area that is strongly affected by mining. Regional departments for land-use planning may use the study outputs in their planning activities in contaminated areas, in urban planning, in meaningful industrialization of rural areas and in decision-making in the field of agricultural production in the Kabwe region.

Acknowledgements

The study originated within the Project of the Development Cooperation between the Czech Republic and Republic of Zambia. Interpretation of results was carried on within the IGCP/SIDA Project 594 “Assessment of impacts of ore mining and mineral processing on the environment and human health in Africa”.

References

CCME (Canadian Council of Ministres of the Environment) (2007) Canadian soil quality guidelines for the protection of environmental and human health. Summary tables, Table 1. Canadian soil quality guidelines. Update 7.0. CCME Otawa, Canada.

Davis, A.., Ruby, M.V., Bloom, M,, Schoof, R,, Freeman, G,, Bergstom, P.D. (1996) Mineralogic constraints on the bioavailability of arsenic in smelter-impacted soils: Environmental Science & Technology 30: 392–399.

Herzman, C. (1995): monitoring of lead concentration in the

Kasanda, Railway and Katonndo townships in Kabwe. – MS. University of British Columbia, Canada.

Salminen, R., Tarvainen, T., Demetriades, A., Duriš, M., Fordyce, FM., Gregorauskiene, V., Kahelin, H., Kivisilla, J. et al. (1998) FOREGS geochemical mapping field manual. – Geological Survey of Finland, Guide 47. Geological survey of Finland, Espoo.

Tembo, BD., Sichilongo, K., Cermak, J. (2006): Distribution of copper, lead, cadmium and zinc concentrations in soils around Kabwe town in Zambia. – Chemosphere 63, 497–501.

ZCCM-IH – Zambia Copper and Cobalt Mining- Investment Holding Plc. (2002): Environmental assessment of the Copperbelt and Kabwe area. MS E 539.- MS ZCCM IH, Nkana, Zambia.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Results of urine and blood from residents around the Copper Smelter Complex, Tsumeb, Namibia: An example of anthropogenic contamination

B.S. Mapani & S. Uugulu
University of Namibia, Geology Department, Private Bag 13301, Windhoek, Namibia, bmapani@unam.na

R. L. Hahn
German Research Foundation, Bonn, Germany

R. Ellmies, N. Mwananawa & William Amaambo
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany

G. Schneider
Geological Survey of Namibia, 1-Aviation Road, Windhoek, Namibia

Abstract. A study of urine and blood samples in 154 and 148 individuals respectively from the Tsumeb area has revealed that there is a direct link between Pb, As, Cd contaminated soils and the levels of these heavy elements in the two selected media. The city of Tsumeb had been a producer of Cu and Zn since 1899 until 1999 when the operation closed. During this period the local smelter produced smoke and fumes that contained among other elements, of note were Pb, Zn, Cu, Cd, As and Co. Upon closure in 1999, the smelter continued to process copper ores from Otjihase, Kombat and Matchless mines. Thereafter in 2006, the smelter began to accept copper ores from beyond Namibia's borders. The effects of the smelter complex was observed in elevated concentrations of the mentioned heavy elements in soils around the town. Pathways of these elements into the human body has been determined as through dust and eating vegetables grown on contaminated soils.

Keywords. Arsenic, lead, cadmium, blood, urine, contamination

1. Introduction

Tsumeb had been a mining town since 1899, when the copper and lead ores were earmarked for mining. In 1907, a smelter was erected and became the source of major anthropogenic pollution. The smelter was replaced by another one in the years 1960-62. By that time Tsumeb had established itself as a major mining town in the then South West Africa. Mining ceased in 1999, when Tsumeb Corporation Limited closed the underground workings. However, the smelter has since been refurbished to modern standards and continues to smelt copper ores from afar fields such as Chile, DRC and Zambia.

This smelting of ores produces fumes which contain some elements deleterious to health, which this paper discusses. The concentration of these ores in soils is a source of direct pollution as a result of either dust generated by children playing or vegetables grown in the soils. This has since been proven in studies conducted by Kribek et al. (2004), Ellmies et al. (2007) and Hahn et al. (2008). In these studies, it was shown that soils are highly contaminated by such metals as Zn, Cu, Pb, As, Cd, and Co, emanating from the roasting of ores in the smelter. The study by Ellmies et al (2007) showed that dust and vegetables were the main pathways for the ingestion of heavy metals in the human body.

This work was specifically done to see how the soil and vegetable contamination correlated with residents in those particular areas of Tsumeb. The map of Tsumeb that is contaminated with Pb is shown in Figure 1. Other thematic maps for Cu, As, Zn, Co were also constructed and showed almost the same pattern.

2 Methodology and Results

The Tsumeb area has been established to contain contamined soil samples around the area west of the smelter complex. The results of a medical test programme of Tsumeb residents are presented. A total of 154 urine samples and 148 blood samples were collected with the assistance of Tsumeb hospital. The blood samples were analysed for lead and cadmium by AAS and the morning urine samples for arsenic and cadmium by ICP-OES. More than a fifth of the investigated residents of Tsumeb showed lead concentrations in blood exceeding the WHO guideline value (10 µg/dL). The highest values for lead in blood (maximum value 55 µg/dL) exceed the WHO limit by more than five times. Statistics show that every sixth surveyed person exceeds the WHO guideline value for arsenic concentration in urine. The highest detected arsenic concentration in urine of 443 µg/L exceeds the WHO limit of 50 µg/L by almost nine times. Nearly all cadmium values in blood were below the detection limit of 0.1 µg/L. The creatinine-adjusted cadmium concentrations in urine with the exception of two cases did not exceed the guideline values. The analytical results correlate for lead in blood and arsenic in urine. Residents with anomalous high concentrations are mainly confined to Tsumeb-Nomtsoub suburb to the west and the industrial zone to the north of the town. Residents of the Transnamib Hostel just opposite the old smelter show the most critical values. The anomalous values could be attributed to inhalation of contaminated dust as well as the contact with contaminated soil and the consumption of contaminated crops as these parts of Tsumeb are more exposed to dust fall-out from the smelter complex than the central and southern parts of the town.

In Figure 1 we show the distribution of residents with Pb levels above the WHO limits. These locations in Figure 1 correlate with the contamination plume in Figure 2.

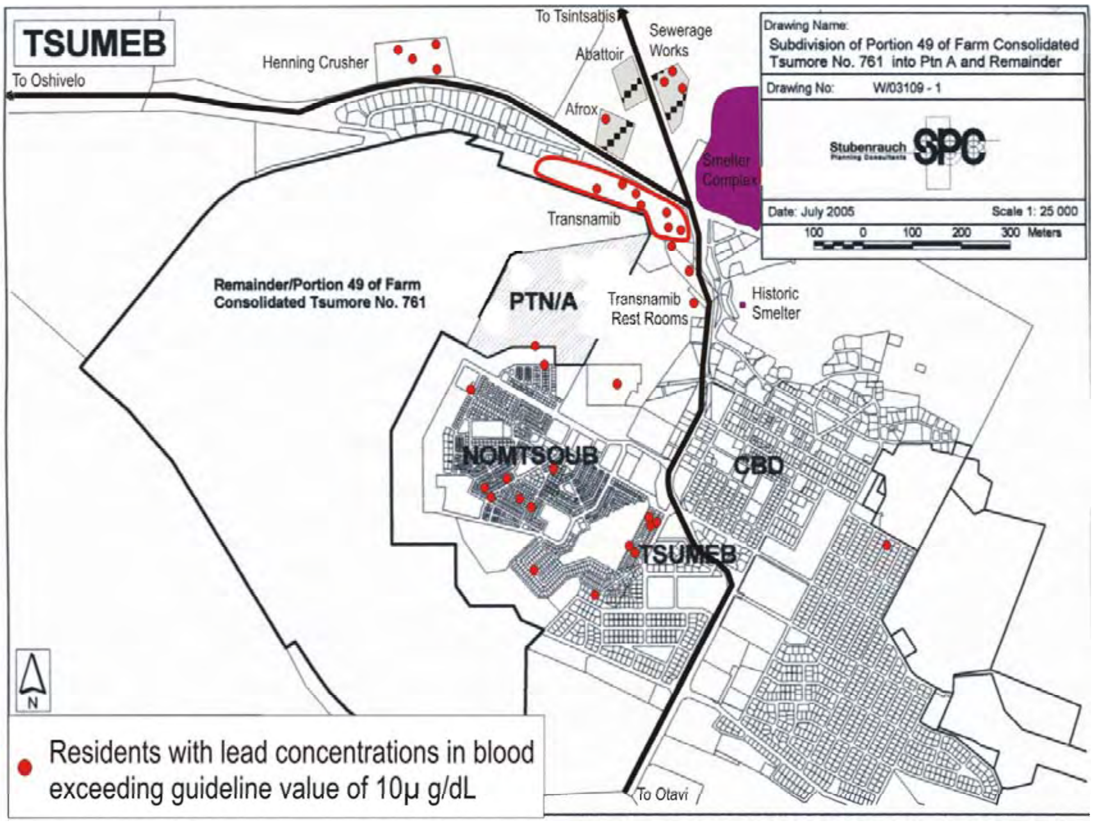

Figure 1. Residents with Pb concentrations exceeding 10 micrograms per decilitre (after Hahn et al., 2008).

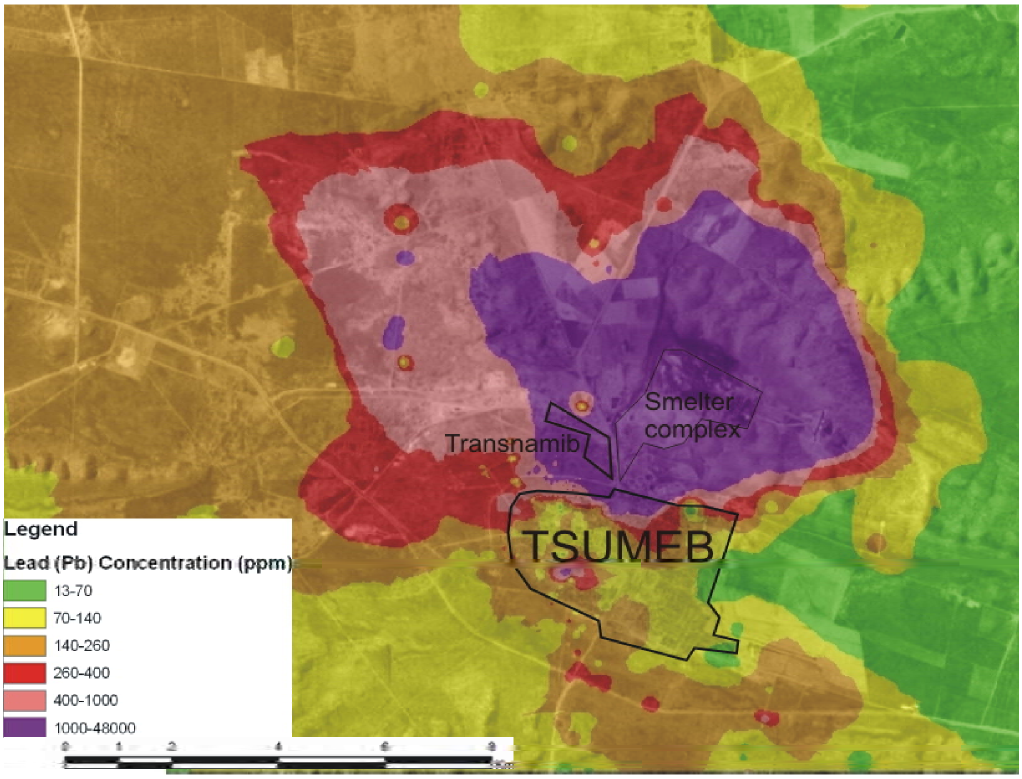

Fig. 2. Lead contamination of surface soils around the Tsumeb smelter (GSN, 2007).

References

Ellmies, R., Mapani, B.S., Hahn, R. L., Ellmies, R., Schneider, G., Mwananawa, N., Uugulu S., and William Amaambo (2007). Investigation of Agricultural Products for Contamination of Toxic Elements in the Surrounding of the Tsumeb Smelter Complex, Environmental Monitoring Series N°11, Ministry of Mines and Energy, Windhoek, December 2007.

Hahn, R. L., Ellmies, R., Mapani, B.S., Schneider, G., Mwananawa, N., Uugulu S. and William Amaambo (2008). Results of Blood and Urine Tests for Heavy Metals in Tsumeb: Environmental Monitoring Series N°12, Ministry of Mines and Energy, Namibia, Windhoek, January, 2008.

Křibek, B, Kamona, F., Knésl, I., Konopásek, J., Majer, V., Pašava, J., Mapani, B., Mwiya, S., Kawali, L., Kandjii, I., Keder, J. and V. Ettler (2005). Assessment of the mining and processing of ores on the environment in the mining districts of Namibia. Final report for the year 2004. - Tsumeb Area. Czech Geological Survey, Record Office - File Report No. 2/2005.

Potential dispersion of toxic elements from mine dumps into surrounding soils in Zimbabwe

Maideyi Meck
Department of Geology, University of Zimbabwe, P.O. Box MP167, Mt. Pleasant, Harare, Zimbabwe, mabvira@science.uz.ac.zw

David Love
WaterNet, P.O. Box MP600, Mt. Pleasant, Harare, Zimbabwe

Benjamin Mapani
Geology Department, University of Namibia, P. Bag 13301, Windhoek, Namibia

Abstract. Zimbabwe has a substantial number of mines working various rock types of various ages.

As many as sixty-seven economic minerals have been mined in the country at one time or another (Bartholomew, 1990a, 1990b). At present forty minerals are being mined (Chamber of Mines database, 2010). The list includes base metals, precious minerals, semi-precious gems, ornamental rocks and industrial minerals. The greater part of the mining production comes from ancient Archean (>2.5 Ga) terrain. These rocks have been worked for gold, silver, iron, copper, nickel, lead, zinc, magnesite, manganese, arsenic, antimony, tungsten, tin, barites, pyrite, corundum, limestone, beryl, tantalum, niobium, lithium, emerald and pollucite. Rocks of Proterozoic age (2.4-0.7 Ga) also host substantial amounts of mineral wealth. The 2,500 Ma Great Dyke is host to chromium, platinum, nickel, copper, gold, graphite and tungsten. Exploitation of such a wide variety of ores, in rocks of diverse composition and age, provides the potential for a great range of environmental pollution problems. Mabvira (2003) notes that Zimbabwe has already suffered a number of mining related pollution and chief among them environmental problems associated with "mine dumps", comprising mill tailings, slimes and waste rock. Most of the dumps contain potentially toxic metals and sulphides that can disperse into the surrounding soils and biota.

The study presented here assessed levels of potentially toxic elements in different types of dumps compared to the soils around these dumps with the objective of ascertaining their potential to disperse and pollute the soils and waters around them.

The study sampled only composite surficial material from each dump. Carbon/sulfur determinator, ion chromatograph, Atomic absorption Spectrometry and Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) were used to determine partial and total elemental concentration. Possible dispersion and pollution patterns likely to result from the tailings dumps' were predicted and modelled using empirical Eh-pH models.

The results indicate significantly higher levels of potentially toxic elements in most dumps compared to the soils around these dumps. The results show that antimony, copper, cobalt, zinc, nickel, arsenic and lead may be problematic in the majority of dumps in Zimbabwe. Whilst effects of antimony, nickel, copper, cobalt, zinc and lead are likely to be significant in acidic dumps, the effects of arsenic are likely to be present in all dump types alkaline and acidic. Antimony, arsenic and lead effects are likely to be localized to the immediate whilst copper, cobalt, zinc and nickel likely to have far reaching effects due to the high mobility. The results from this study give a general indication of the state of the dumps in Zimbabwe with regards to the levels of potential toxic elements and concludes that a high likelihood of continual production of acid in most dumps and potential to release bio-available forms from the dumps into the surrounding environment.

The empirical Eh-pH models show how and under what conditions the metals/elements released will disperse from the dumps. Likely destinations for the contaminants are also predicted. In the models the equilibrium chemical species in the dumps are predicted for the pH environment in terms of the nature of the species (solid, solution or gas) likely to exist under each pH environment. The distribution and/or dispersal of individual pollutant are then derived. The dispersion/distribution used here is in the form of soluble ions. The solid states are assumed to be stable and unlikely to disperse while the gaseous states though known to disperse are assumed to affect a different environment. The Eh-pH diagrams in this study have been extended to Eh 1.2 and cover the whole pH range because dump conditions are not natural conditions hence Eh is expected to be outside normal Eh ranges.

Keywords. Toxic elements dispersion, mine dumps, Zimbabwe

References

Bartholomew, D.S. (1990a). Base Metal and Industrial Deposits of Zimbabwe. Zimbabwe Geological Survey. Mineral Resources Series No. 22.

Bartholomew, D.S. (1990b). Gold Deposits of Zimbabwe. Zimbabwe Geological Survey. Mineral Resources Series No. 23.

Mabvira, M.L. (2003). A GIS based study of the dispersion of toxic elements from mining activities in Zimbabwe into soils and water systems. Unpublished MPhil thesis University of Zimbabwe Geology Department

Meck, M.L. Love, D, Mapani B. (2006). Zimbabwean mine dumps and their impacts on river water quality – a reconnaissance study Physics and Chemistry of the Earth 31, 797–803.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Risk assessment of abandoned mine sites in Namibia

Kaarina Ndalulilwa, Alina Haidula & Rosina Leonard
Geological Survey of Namibia (GSN), Ministry of Mines & Energy (MME), kndalulilwa@mme.gov.na

Rainer Ellmies
The Federal Institute of Geosciences and Natural Resources (BGR), Hanover, Germany

Abstract. Early mining activities in Namibia, and subsequent beneficiation processes have been conducted with little to no regards for the environment, thus leaving the land with un-rehabilitated abandoned mines. The abandoned mine sites pose environmental problems such as collapse of structures, contamination of groundwater and soil and subsequently effects to livestock and human health.

An inventory with 157 abandoned mines has been compiled through the BGR-GSN project of technical cooperation. Of the 157 mines, detailed environmental monitoring has only been carried out at few of these abandoned mines by soil, stream sediment, water sampling and partly radiation.

In 2010, a “Risk Assessment Manual” developed for the Chilean government was adapted and customized into the Namibian situation, taking into account specifics of the minerals mined in the past in Namibia, beneficiation processes, as well as the environmental and the legal situation. The manual prioritizes the risk potentials. Accordingly, the Namibian government can start with mitigation of the most severe hazardous risks.
The manual includes guidelines for assessing safety and contamination risks, with further detail of classifying the risk according to the geological and physical situation on the ground.

Keywords. abandoned mine sites, risk assessment, Namibia,

1 Introduction

Mining in Namibia dates as far back as more than 400 years ago, as evidenced from archeological work of copper smelting at the Matchless mine, located about 40 km west of Windhoek. Even long before mining technology was introduced, Namibians have been smelting copper in anthills, with aid of charcoal, in the Otavi Mountainland (Schneider, 1998). Following the publication titled “Travels in Tropical Africa”, in 1852 by Sir Francis Galton, in which he mentions encounters with various Bushmen and Owambo who were transporting copper ore in the Otavi Mountinland; a port was soon after established at Walvis Bay and exploration and mining activities commenced in Namibia (Cairncross, 1997). Since then widespread deposits have been mined all over Namibia. These were mainly for base metals, precious metals, precious stones (mainly diamonds) and industrial minerals (mainly salt).

Early exploration and mining activities were conducted with little regard for the environment. Once an economic deposit was discovered, ore extraction was mainly aimed at mining out as much of the ore as technologically possible at as many sites as possible without any remedial measures undertaken. Extraction methods used then, were not always efficient in the recovery of commodities and therefore large quantities of ore were at times discarded in tailings or with slag creating further sources of contamination. This is a problem that has been left for the shoulders of the current generation of Namibians and its government. Rehabilitation is an expensive task, and makes rehabilitation only possible in extremely limited numbers. Therefore, a prioritization of risks is a prerequisite for decision makers to eventually go ahead with site-specific rehabilitation.

The legacy of this long mining history is an inventory of 157 abandoned mine sites countrywide, on which no remedial measures have been undertaken (Fig. 1). This is a problem that now lies on the shoulders of the Namibian government. The current costs of mine site rehabilitation, coupled with inadequate funds and limited knowledge, makes rehabilitation in many cases impossible.

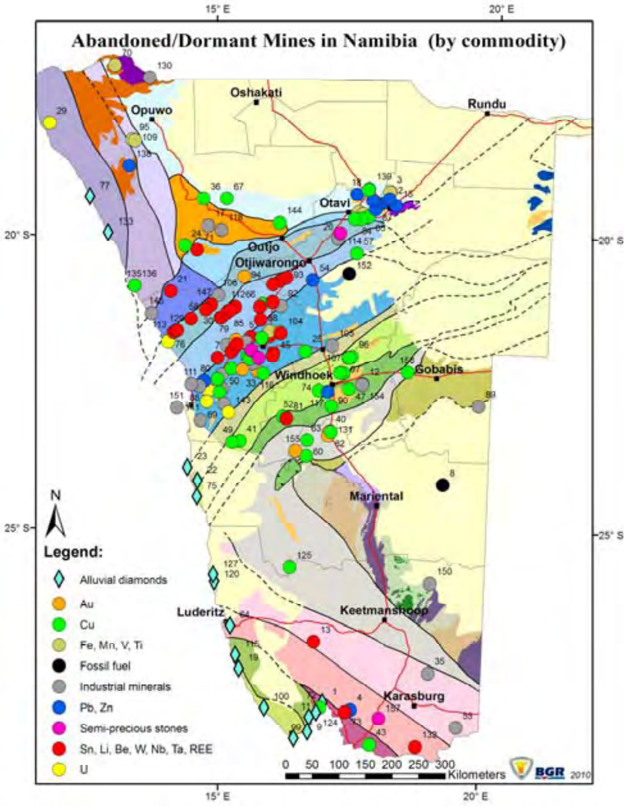

Figure 1. Location of known Abandoned Mines Sites in Namibia.

2 Environmental Monitoring of Abandoned Mine Sites

The government of Namibia has become aware of the dangers posed by uncontained mining related activities, and has put in place facilities to deal with both past and active mining environments in Namibia. For instance the Mining Directorate in the Ministry of Mine Energy has the task to oversee that mineral resources are exploited in a safe, responsible and sustainable manner. To achieve this task the directorate undertakes to proactively develop and implement environmental policies to minimise the impact of the exploitation of Namibia's mineral resources, and to promote, monitor and ensure safe and healthy conditions for mining industry employees and the public.

3 Risk Assessment Manual of Abandoned Mine Sites in Namibia

Risk assessment of abandoned mines must be undertaken in a systematic way, such that the data may always be used as a baseline for further monitoring. To this effect a “Risk Assessment Manual” developed for the Chilean government was adapted and customized into the Namibian situation, taking into account specifics of the minerals mined in the past in Namibia, beneficiation processes, as well as the environmental and the legal situation. The risk assessment manual was produced by highly recognized specialists in the various fields of environmental aspects and supported by the BGR-GSN Technical Cooperation Project.

The manual prioritizes the risk potentials and accordingly triggers mitigation of the most severe hazardous risks. It includes guidelines for assessing safety and contamination risks, with further detail of classifying the risk according to the geological and physical situation on the ground. Evaluating the risk of abandoned mine site starts by carrying out a desktop study, which is followed by a simplified risk assessment for safety and contamination at the site, and if necessary, a detailed risk assessment. This will lead to classification and prioritization of abandoned mine site according to the identified risks.

The manual also includes sample forms in which different components of the mine (generally all works, installations, support services and infrastructure necessary for mining operations) are listed so that appropriate evaluation is always carried out in a systematic way according to guidelines, which further make it easier to incorporate the collected data into a database. The manual classifies risks of contamination and risk to safety from past mining sites that are evaluated in terms of sources, exposure pathways and receptors (eg. humans and the environment).

A simplified practical training exercise on the manual has been carried out at three mine sites in Namibia with subsequent re-customization.

4 Conclusion

Of the 157 abandoned mine sites in Namibia in the inventory, only a handful has been monitored to determine their contamination and safety risks. These monitoring activities have been carried out in a detailed risk assessment. The Ministry of Mines and Energy continues to monitor the abandoned mines of Namibia in a systematic way according to guidelines in the Risk Assessment Manual. As the government is not able to rehabilitate all mine sites cheaper alternatives for rehabilitation are sought.

The “Risk Assessment Manual for Abandoned Mine Sites” represents a scientific and practical basis for the evaluation of risks at abandoned mine sites. The manual which has been customized for the Namibian context can be further developed and customized with little to moderate effort for any other country.

Acknowledgements

Bryony Walmsley of the Southern African Institute of Environmental Assessment (SAIEA), Dr. Willie van Niekerk of Infotox (Pty) Ltd, and Peter Terbrugge of SRK Consulting, are thanked for the excellent work done during the customization of the “Risk Assessment Manual of Abandoned Mine Sites in Namibia”.

References

BGR/GSN/SERNAGEOMIN, 2010, The Risk Assessment Manual of Abandoned Mine Sites in Namibia, Ministry of Mines and Energy, Namibia.

Cairncross, B., 1997, The Otavi Mountain Land Cu-Pb-Zn-V deposits: Namibia, Mineralogical Record, Volume 28, pg 109-130.

Schneider, GIC, 1998, The History of Mining in Namibia, Namibia Brief, No. 21, pg 19-31.

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Potential adverse health effects of environmental and occupational exposure to minerals containing cobalt and associated metals

Benoit Nemery
Occupational, Environmental & Insurance Medicine, Department of Public Health, K.U.Leuven, B-3000 Leuven, Belgium
ben.nemery@med.kuleuven.be

1 General consideration

For centuries, metals have been known to be capable of causing human disease. The human toxicity of the so-called “heavy metals”, i.e. lead (Pb), mercury (Hg) and cadmium (Cd), is well established, as is the toxicity of the metalloid arsenic (As). These elements exert no beneficial effects on human biochemistry or physiology and, hence, adverse effects may already occur at very low levels of exposure. In contrast, some metals (or metalloids), notably iron (Fe), copper (Cu), zinc (Zn), cobalt (Co), selenium (Se) and manganese (Mn), are essential for several metabolic processes. Consequently, human disease can result from deficiencies in these essential metals. For example, anaemia may be caused by iron deficiency (e.g. through chronic blood loss), or by dietary deficiency or malabsorption of vitamin B12 (which contains Co). However, even essential metals are not devoid of human toxicity when they are present in excessive quantities in the body. Generally, essential metals will cause harmful effects at higher levels of exposure than non-essential metals.

In addition to the dose (i.e. the quantity that is absorbed), the toxicity of metals is dependent on factors related to the agent (speciation, physical and chemical properties), the exposure conditions (route of exposure, intensity of exposure, concurrent exposures, ...) and the individual susceptibility (age, genetics, concomitant disease, ...). The mechanisms for the cellular toxicity of metals include binding to critical functional groups (e.g. sulphydryls) on proteins or DNA, as well as oxidative stress caused by the ability of transition metals to change their oxidation state, thus producing toxic oxygen species.

People are rarely exposed, in a toxicologically significant way, to the pure metallic form (zero oxidation state) of metals or metalloids, except in the case of Hg vapours (relevant for those using Hg to purify gold). More usually, there is exposure to more or less soluble oxides or other binary metal compounds (sulphides, halides, hydrides, carbides) or to multielement compounds (mainly salts). Metals, most notably transition metals, can form co-ordination complexes with various ligands such as ammonia (NH3), carbon monoxide (CO), cyanogen (CN-), organic nitrogen or sulphur molecules.

Some metals may also form organometallic compounds in which the metal is bound to the carbon atom of an organic group.

It is important to realize that during mining and at various stages in the purification of metal-containing minerals or ores, there is generally also considerable exposure to many hazardous non-metallic components. The most important examples are crystalline silica (SiO_2) in dust from mines or quarries, and sulphur dioxide (SO_2) in some metallurgic processes. Consequently, disease in metal miners or people involved in the transformation of metals is not necessarily related directly to the metals that are being mined or purified. Thus, miners are at risk of silicosis if the rocks contain a lot of quartz, especially if mechanisation leads to the production of a lot of fine dust particles. Another complicating issue is that toxic agents may cause diseases that resemble “naturally” occurring disease, thus rendering it difficult to make a correct diagnosis in affected individuals.

Metallic agents may enter the body through various routes: via inhalation, via oral intake and through the skin. Absorption of metals through the skin is generally not very important. Oral intake occurs when contaminated water or foods (vegetables, fish, meat, ...) are consumed and, especially in young children, when dust-contaminated hands or objects are put in the mouth; sometimes traditional medicines may contain toxic metals. Inhalation of metal-containing dust is an important route, especially in the workplace. Particles are most likely to penetrate (and remain) deep into the respiratory tract if they are very small (diameter < 2.5 µm).

Exposure to metals may be assessed by measuring the concentration of metals in various environmental compartments (air, drinking water, food) and estimating the amount of material inhaled and/or consumed over a defined duration. However, this process is often complex and fraught with many uncertainties. A convenient alternative to assess overall exposure is to perform biomonitoring, i.e. measuring the concentration of metals in urine, blood or other body compartments, such as hair. The information gained from such biomonitoring, however, depends on the toxicokinetics of the metal in the human body. Thus, some metals accumulate in the body (e.g. Cd, Pb), whilst others are eliminated more or less rapidly (e.g. As, Co, Hg). In the latter case, the values obtained are greatly dependent on the interval between blood or urine sampling and exposure. Concentrations of metals in urine may be expressed as µg/L, but they are generally corrected for dilution by expressing values as µg/ g creatinine, because the amount of creatinine excreted per day is relatively constant.

In the following paragraphs, the most relevant human effects of copper and cobalt, the main metals mined in the African Copperbelt, will be summarized first; then the health effects of the other associated metals will be briefly summarized. However, it must be recognized that our knowledge of the human toxicity of some of these elements is often very limited, especially with regard to chronic exposure of the general population (that includes children, pregnant women and elderly persons) or individuals with malnutrition or chronic infections. Moreover, we generally know very little about the health effects of combined exposures to different metals and/or other non-metallic agents.

2 Specific metals

2.1 Copper

Copper (Cu) is an essential nutrient because it is a coenzyme for various enzymes. In blood, Cu is mainly bound to a transport protein, caeruloplasmin. Cu is excreted mainly through the bile, and only a small proportion is excreted in urine. Cu has a relatively low toxicity for humans. Acute exposure to Cu fumes (e.g. during smelting) may cause metal fume fever, a condition that resembles malaria or flu. Gastrointestinal disturbances are caused by ingestion of drinking water containing 4 mg Cu/L or more. Chronic overexposure to Cu is associated with progressive liver damage. Wilson’s disease is a rare genetic disorder in which Cu accumulates in the liver.

2.2 Cobalt

Cobalt (Co) is a constituent of vitamin B12 and is, therefore, an essential nutrient. Inhalation of Co-containing dusts may lead to rhinitis, bronchitis, bronchial asthma and, in some circumstances, lung fibrosis. The latter condition has been described almost exclusively in workers handling hard-metal [a composite of tungsten carbide (WC) and Co] or diamond-cobalt tools. Co may also cause allergic contact dermatitis (eczema). In the 1970s, several outbreaks of cardiomyopathy were attributed to the addition of Co salts to beer; however, the effects of environmental exposures to Co on the heart muscle remain to be established. Co is known to affect the thyroid (causing thyroid hyperplasia) and the blood (causing polycythaemia) but, again, these effects need to be studied more extensively in populations that are environmentally exposed. There is no long-term accumulation of Co in the body, and Co is rapidly excreted in the urine. In unexposed people, the concentration of Co is < 2 µg/g creatinine and the concentration in blood is < 1 µg/L. The Biological Exposure Index (BEI) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) is 15 µg/L urine at the end of a work shift at the end of a workweek, corresponding to an atmospheric exposure level of 0.02 mg/m3 (Threshold Limit Value – Time-Weighted Average over 8 h).

2.3 Lead

Lead (Pb) is a well-established toxic metal that may affect the central and peripheral nervous system, the blood, the kidney, the cardiovascular system (hypertension), the gastrointestinal tract, and male reproduction. Even a low exposure to environmental Pb (originating from the use of leaded petrol) has been associated with adverse effects on the mental development of infants and young children. The most appropriate biomarker of exposure to Pb is the concentration of Pb in blood, which reflects a combination of the past exposure during the last months and several years back in time. A significant source of occupational and environmental exposure to Pb consists of the (artisanal) repair of car radiators and batteries.

2.4 Cadmium

Cadmium (Cd) has a very long biological half-life (10-20 years) in the body because it accumulates in the liver and kidneys. Substantial exposure to Cd may occur in the workplace, but also through environmental pollution around non-ferrous mines and metal refining industries, which results in high concentrations of Cd in foodstuffs (rice, shellfish, some leafy vegetables). Long-term exposure causes kidney damage and bone demineralization (osteoporosis). The concentration of Cd in urine is a good reflection of the body burden, with 5 µg/g creatinine being considered too high.

2.5 Arsenic

Inorganic arsenic (As) occurs as an impurity in the ores of non-ferrous metals. In some areas (most notably Bangladesh), very high levels of As may be present in wells. Chronic exposure to inorganic As affects many systems of the body, causing skin diseases (hyperpigmentation, hyperkeratosis, skin cancer), sensorimotor polyneuropathy, heart and circulatory disease, liver cirrhosis and cancer of the liver, lung and bladder. Exposure to As has also been associated with diabetes and adverse reproductive outcomes. Inorganic As is biotransformed (by methylation) and excreted relatively rapidly (half-life of about 60 h) in the urine. Certain sea fish and crustaceans contain very high levels of organic As; this organic As is not harmful, but the ingestion of seafood may greatly influence the urinary concentrations of As. The concentration of As in hair or nails reflects the exposure over a few months.

2.6 Manganese

Manganese (Mn) is considered relatively non-toxic, but high occupational exposure to MnO2 (in miners, smelters, steelworkers and welders) can cause serious disease of the respiratory tract and of the central nervous system. “Manganism” is a condition that resembles Parkinson’s disease and is characterized by slowly progressive neurological and psychiatric dysfunction. Biomonitoring has not yet proven helpful in the surveillance of Mn-exposed workers.

2.7 Molybdenum

Molybdenum (Mo) is a metal for which only little human toxicity data are available. Acute exposure to MoO3 causes mucosal irritation. Some evidence indicates that Mo may be a male reproductive toxicant.

2.8 Nickel

Nickel (Ni) is mainly known for its potential to cause allergic contact dermatitis, and also for the marked increase in nasal sinus and lung cancer observed among workers involved in Ni refining.

2.9 Tin

Tin (Sn) is not an essential metal. Long term exposure to Sn dust or fumes results in accumulation of Sn in the lung tissue and thus leads to a pneumoconiosis called "stannosis". Inorganic Sn compounds are very poorly absorbed by the gastrointestinal tract, and no systemic effects have been described to result from chronic exposure in humans.

2.10 Vanadium

Vanadium (V), as V_2O_5, may cause mild to severe irritation of the eyes and the respiratory tract. V does not have known systemic toxic effects in humans. Exposure to V can be reliably assessed by urinary biomonitoring.

2.11 Uranium

Uranium (U) exists under three natural isotopes (234U, 235U, 238U), with 238U being the most abundant isotope (>99% by mass), and 235U (0.7% by mass) being the isotope that is used (after enrichment) as a source of energy for nuclear reactors and weapons. Although U is both a chemical and a (weakly) radioactive material, its adverse health effects result primarily from its chemical toxicity rather than its radiotoxicity. Absorption of U is low by all routes. The main target organ is the kidney, where U accumulates. There are no human data to suggest that U itself causes cancer or affects human reproduction. Urinary biomonitoring can be used to assess exposure. In a representative sample (n=2689) of the general population of the USA, the median concentration of U in urine was 0.007 µg/g creatinine, with a 95th percentile of 0.040 µg/g creatinine.

2.12 Zinc

Zinc (Zn) is a ubiquitous element that is essential for life. Zn-deficiency occurs in populations with diets poor in animal flesh, because plants are rich in indigestible Zn-binding ligands. Manifestations of Zn deficiency include mainly reproductive effects (abortions, teratology, prematurity and retarded foetal growth). Human Zn toxicity is infrequent. Exposure to high concentrations of Zn fumes (ZnO_2) leads to metal fume fever. Urinary Zn excretion is decreased in Zn deficiency and increased in Zn excess.

References

Nordberg, G.F., Fowlwe, B.A., Nordberg, M., Friberg, L.T. (Eds.). (2007). Handbook on the Toxicology of Metals (3d Edition). Elsevier – Academic Press, [ISBN 978-0-12-369413-3]

Baxter, P.J., AW, T.-C., Cockcroft, A., Durrington, P., Harrington, J.M. (Eds.) (2010). Hunter's Diseases of Occupations (10th edition). Hodder Arnold, [ISBN 978-0-340-9-41669]

Nemery, B. (1990). Metal toxicity in the respiratory tract. European Respiratory Journal, 3, 202-219.

Analytical studies of metallophytes that grow in Cu-Ni mineralised areas in Botswana

Bonang B.M. Nkoane
Department of Chemistry, University of Botswana, Private Bag UB 00704, Gaborone, Botswana
(*bonang.nkoane@mopipi.ub.bw*)
Walter Lund, Grethe Wibetoe
Department of Chemistry, University of Oslo, P. O. Box 1033, N-0315 Oslo, Norway
Nelson Torto
Department of Chemistry, Rhodes University, P. O. Box 94, Grahamstown 6140 South Africa

Abstract. Plant species that accumulate high levels of metals in proportion to the metal content in the soil are of considerable interest in biogeochemical and biogeobotanical prospecting as well as phytoremediation. *Helichrysum candolleanum Blepharis aspera and Blepharis diversispina* that grow in copper-nickel mineralised area in the northeastern part of Botswana were studied using various analytical techniques. Ultrasonic slurry sampling electrothermal atomic absorption spectrometry (ETAAS) was employed for rapid total metal determination of copper and nickel in small amounts of the both soils and the respective plant parts (roots, stem, leaves and flowers). All plant species showed tolerance towards high concentrations of metals and were thus categorized as metallophytes. The leaf-to-shoot ratio suggested that *H. candolleanum* has a tendency to take up metals and transfer them to the higher parts. Furthermore, a multielement study employing inductively coupled plasma atomic emission spectrometry (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS) showed that the three plants showed different metal distribution patterns and levels. Speciation studies of the water extracts of roots, stems and leaves *B. aspera*, and *H. candolleanum* were analysed using ICP-MS in combination with cation exchange solid-phase extraction (off-line) and on-line with size exclusion chromatography (SEC) also suggested different tolerance mechanisms. It was concluded that*, of* the three plants, *H. candolleanum* could be a possible copper/nickel indicator plant in biogeochemical or biogeobotanical prospecting.

Keywords. *Helichrysum candolleanum; Blepharis diversispina*; *Blepharis aspera*, Cu-Ni indicator plants; Metallophytes, Slurry sampling ETAAS, ICP-MS, ICP-AES, SEP/SEC-ICP-MS

1. Introduction

In the last two decades, metallophytes, i.e. metal-tolerant plants that grow in mineralized soils, have received attention because of their potential use in phytoremediation, such as in rhizofiltration, phytostabilization, phytovolatization and phytoextraction processes (Van der Lelie *et al.*, 2001; Adriano *et al.*, 2004; Vassilev *et al.*, 2004) and mineral exploration, such as geobotanical and biogeochemical prospecting (Dunn *et al*. 1996; Brooks 1998).

Phytoremediation related investigations are of paramount importance especially in developing countries and consequently the area of sample preparation for plant and soil samples with subsequent speciation analysis is seen as an important area that will see rapid growth in the future. As such, the Chemistry Departments at the University of Botswana and the University of Oslo has been engaged in a collaborative project between in studying metallphytes from Cu-Ni mineralized areas in Botswana. Analytical methodologies were developed for determinations of total metal concentrations as well as speciation, to try to understand the tolerance mechanisms.

2 Experimental

2.1 Sampling and samples

All plants and soils were collected from four Cu– Ni mineralized areas in the North-Eastern part of Botswana as indicated in the map of Botswana (Fig. 1). Three types of plants were collected, i.e., *Helichrysum candolleanum Blepharis aspera and Blepharis diversispina* (Fig. 2). The plants were washed with deionised water and air dried before being ground in a mixer mill to a fine powder (~63µm).

Legend: A: Selkirk, about 35 km north east of Francistown; GPS location: S 21° 18´, E 27° 44´, Altitude: 1018 m. B: Nakalakwana, about 60 km from Francistown, along Francistown-Orapa road; GPS location: S 21° 05´, E 26° 59´, Altitude: 1117 m. C, D: Thakadu and Malaka, respectively, are about 82 km from Francistown, 5 km off Francistown Orapa road, and 2 km apart

Figure 1. Map of Botswana showing four sampling sites from North-Eastern part of Botswana.

A: *H. candolleanum* (from Thakadu)

B: *B. diversispinia* (From Malaka)

C: *B. aspera* (from Selkirk)

Figure 2. Photographs of plants under study.

2.1 Analytical procedures

2.1.1 Slurry sampling ETAAS

Reference and sample materials (soil or plant of particle size less than 63 µm) were accurately weighed (1.0–4.0 mg) into the 2 ml autosampler vials and 1 ml of the diluent (5% (v/v) HNO3 and 0.05% Triton X-100) was added. Before injection into the graphite furnace, the samples were manually homogenized using a hand held ultrasonic probe (30 W, 25 s). Five individual slurry preparations (n =5) were analysed for each sample material (Nkoane et al., 2005)

2.1.2 Multielement determination

Sample decomposition digestion took place in closed vessels in the microwave oven (see Nkoane et al., 2007 for full description of the method). After decomposition, a total of 62 elements were studied in the plant parts and their host soils using ICP-AES and ICP-MS.

2.1.3 Speciation procedures

Water extracts of plant samples were passed through a strong cationic exchange (SCX) solid phase catridge and the eluent analysed for metals. The non-retained metals, i.e., non-cationic species were then used for determination on non-cationic species (Nkoane et al., 2011). For the SEC-ICP-MS experiments, water extracts were injected into a calibrated SEC column (with globular protein standards (6.5–67 kDa) and sodium polystyrene-4-sulphonate standards (4.3–13 kDa), each injected separately) with a 0.2 M ammonium acetate as the mobile phase. The eluent of the SEC column was monitored with UV at 254 nm and passed on for ICP-MS qualitative metal detection. Details of the procedures are in Nkoane et al. 2011.

3. Results

From the ultrasonic slurry sampling ETAAS method that was used to determine Cu and Ni in soils and plants parts, the results showed that all the three plants plants had metals concentrations higher than concentrations normally found in plants and therefore should be categorized as metalophytes. *H. candolleanum* had tendency to take up and translocate the metals to the shoot while *B. aspera* seem to restrict the metals to the lower parts, especially when the soil metal concentration was high (see Fig. 3 for Cu).

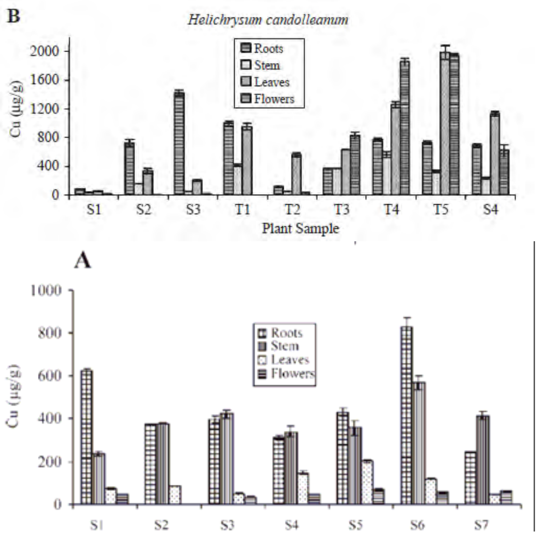

Figure 3. Cu concentrations in plant parts of *B. aspera* (A) and *H. candolleanum* (B), arranged according to increasing soil metal concentration from left to right.

The multielement study revealed that the metallophytes under study accumulated other metals, other than Cu and Ni, see Table 1 for *H. candolleanum* leaves (Nkoane et al., 2007).

The presence of organic matter associated with metals previously found in higher than normal amounts in these plants were investigated. Ultrasonic-assisted water extracts of the roots, stem and leaves of the plants were analyzed by SEC–UV–ICP–MS (Nkoane at al., 2011) to obtain information about the molecular sizes of the metal complexes; and off-line solid-phase extraction with strong cation exchange was used to determine the charge of the species. Fig. 4 shows a size exclusion chromatogram of water extracts of *H. candolleanum* leaves, the organic material detected at 254 nm and the elements detected from an on-line SEC–ICP–MS system. The plant extracts from all plant parts, for both plants, showed a pattern that was similar to the chromatogram in Fig. 4. The molecular weight distribution of the metal species was somewhat different for the two metallophytes, *B. aspera* and *H. candolleanum*, despite similar UV chromatograms.

Table 1: Metal concentrations (**Bold** numbers represent concentrations more than 10 times higher than normal) with the standard deviations (n=3, in µg/g) of plant parts of *H. candolleanum* and the host soils.

Plant	**Elemental concentration (mean ± SD) µg/g**									
H. candolleanum	**Ba**	**Cd**	**Co**	**Cr**	**Cu** *	**Ni**	**V**	**Ti**	**Al***	**Fe** *
a) Selkirk										
Soil	170±6	0.1±0.01	71±2	160±8	**16±0.5**	**1400±11**	26±0.8	410±5	82±7	70±4
Root	23 ± 1	4.7±0.1	4.8±0.1	4.8±0.002	**0.9±0.04**	41 ± 0.4	1.1±0.004	**58 ± 0.3**	0.7±0.03	1.1±0.06
Stem	8 ± 2	12±1	5.6±0.2	2.5±0.08	**0.2±0.005**	21 ± 0.5	0.8 ± 0.09	**69± 5**	0.3±0.02	0.6±0.03
Leaves	19±0.04	21±0.5	18±0.4	21±0.4	**1.5±0.06**	**110 ± 1**	4.4 ± 0.2	**230±10**	**3.3±0.1**	**5.5±0.2**
b) Thakadu										
Soil	3.4±0.2*	0.9±0.03	7.8±0.4	67±3	**39±1**	18±0.1	54±4	1300±50	16±0.5	46±0.7
Root	**2.9±0.1b***	4.8±0.1	0.3±0.09	2.7±0.4	**1.2±0.002**	2.4±0.3	**6.3±0.07**	35±1	0.3±0.02	0.7 ± .03
Stem	**2.4±0.1***	23±0.9	0.9±0.07	10±0.9	**0.7 ± .002**	5.7±0.09	**7.9 ± 0.9**	**150±1**	0.4±0.01	1.0±0.07
Leaves	**2.3±0.4***	22±1	4.4±2	29±0.6	**2.2 ±0.04**	7.2±0.6	**31 ± 0.3**	**390±6**	**1.8±0.03**	3.0±0.02

* Concentration in mg/g

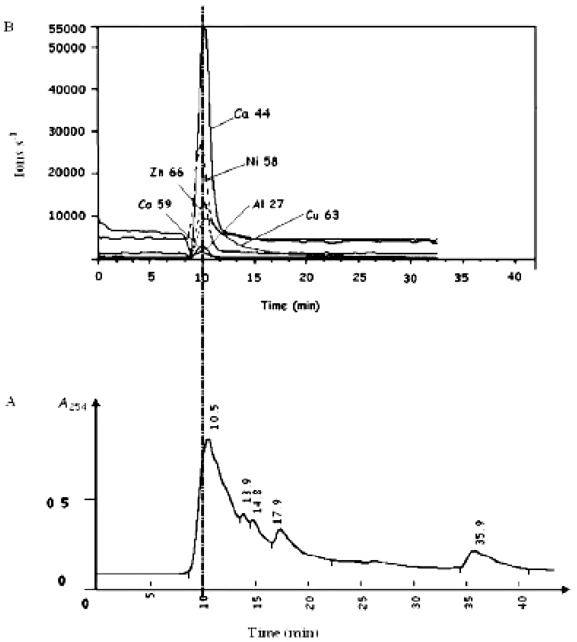

Figure 4. (**A**) Size exclusion chromatogram of water extracts of *H. candolleanum* leaves. Mobile phase: 0.2 M acetate buffer (pH 4.6). Organic material detected at 254 nm. (**B**) Elements detected from online SEC-ICP-MS. The vertical stippled line indicates the retention time of 10 min.

4. Conclusion

Analytical methodologies were developed for studying metal accumulation in three metallophytes (*Helichrysum candolleanum Blepharis aspera and Blepharis diversispina)*. Total metal determination was achieved through a simple, rapid method – slurry sampling ETAAS. Metal species in water extracts were performed by employing offline SPE and online SEC-ICP-MS, which showed the potential to use this combination of techniques for metal speciation, which is viewed to be an important future practice especially that legislators increasingly require more information about the available metal species. Of the three plants, *H. candolleanum* has been identified as a possible as a copper/nickel indicator plant in biogeochemical or biogeobotanical prospecting.

5. Acknowledgements

The authors are grateful for the financial assistance received from the Norwegian Universities Committee for Development Research and Education (NUFU), Norway.

6. References

Adriano, D.C., 2001. Trace Elements in Terrestrial Environments: Biochemistry, Bioavailability and Risks of Metals, 2nd ed. Springer-Verlag, New York.

Brooks, R.R., 1998. Biogeochemistry and hyperaccumulators. In: Brooks, R.R. (Ed.), Plants that Hyperaccumulate Heavy Metals. CAB International, Oxon UK, pp. 95–118.

Dunn, C.E., Brooks, R.R., Edmondson, J., Leblanc, M., Reeves, R.D., 1996. Biogeochemical studies of metal-tolerant plants from Southern Morocco. J. Geochem. Explor. 56, 13–22.

Nkoane, B. B. M., Sawula, G. M., Wibetoe, G., and Lund, W. 2005. Identification of Cu and Ni indicator plants from mineralized locations in Botswana, *Journal of Geochemical Exploration*, 86, 130–142.

Nkoane, B. B. M., Lund, W., Wibetoe, G., and Torto, N. 2007. A multielement study on metallophytes from mineralized areas in

Botswana using ICP-AES and ICP-MS, *Geochemistry Exploration, Environmental Analysis*, 7, 49–56.

Nkoane, B. B. M., Lund, W., Wibetoe, G., and Torto, N. 2011. Studies of metal species in water extracts from metallophytes employing solid phase extraction and size exclusion chromatography coupled to inductively coupled plasma mass spectrometry, *Geochemistry Exploration, Environmental Analysis,* 11,1–8.

Van der Lelie, D., Schwitzguebel, J.-P., Glass, D., Vangronsveld, J., Baker, A., 2001. Assessing phytoremediation's progress in the United States and Europe. Environ. Sci. Technol. 35, 446A–452A.

Vassilev, A., Schwitzguebel, J.-P., Thewys, T., Van der Lelie, D., Vangronsveld, J., 2004. The use of plants for remediation of metal contaminated soils. Sci. World 4, 9–34.

A new strain of *Comamonas Testosteroni* isolated from heavy-metal contaminated site in the Zambian Copperbelt: Adaptation to cobalt and other heavy metals

Alakendra N Roychoudhury
Department of Earth Sciences, University of Stellenbosch, Stellenbosch, South Africa, roy@sun.ac.za

Sarah Staniland
Department of Physics and Astrononmy, University of Leeds, Leeds, UK

Don Cowan
Institute for Microbial Biotechnology and Metagenomics, University of The Western Cape, Belville, South Africa

Abstract. A biogeochemical study of a polluted wetland site in Kitwe, Zambia shows high concentration of trace metals (e.g., > 25 and≈ 2 fold higher than the Eco-toxic threshold values of copper and cobalt, respectively) with many sequestered with the sediment organic phase. Depth profiles in surface sediments suggest trace metal cycling between porewater and solid phases, including that of cobalt. This study documents a bacterium displaying resistance to, and accumulation of cobalt, and that cobalt has a positive effect on growth. The isolate was enriched from the microbial community and identified using 16S rRNA gene sequence analysis as a strain of *Comamonas testosteroni* (designated *C. testosteroni* TDKW). Improved growth of *C. testosteroni* TDKW was seen with the addition of up to 200 μM cobalt (optimal growth ca. 100 μM), while concentrations above 4 mM completely inhibited growth. *C. testosteroni* TDKW also exhibited resistance to high concentrations of iron and manganese, but showed limited resistance to copper or nickel. Further analysis revealed cellular cobalt accumulation and the presence of heavy-metal resistance genes, tentatively suggesting that this organism could contribute to *in situ* biological cycling of cobalt in mineral contaminated aquatic systems.

Keywords. *C Testoseroni*, Zamiba, Kitwe, cobalt, eco-toxicity, trace metal cycling

1 Introduction

Metallophiles, bacteria capable of growing in a more metal rich environment than *E. coli* (Nies 1999; 2000), play an important role in the speciation and mobility of metals (Wood 1987). The metal uptake capabilities of these organisms and their resistance to high metal concentrations make them suitable for bioremediation and bioleaching applications. As such, there is increasing research interest in the mechanisms of microbial bioremediation in complex communities such as constructed wetlands (Kosolapov et al. 2004), as well as in the mechanisms of resistance, uptake and mineral cycling (Nies 1999).

The identification of microbial species present in heavy metal contaminated sites is a preliminary step in developing an understanding of the microbial processes *in situ*. In this study, a bacterial isolate identified by 16S rRNA gene sequence analysis as *Comamonas testosteroni* was found to be a culturable aerobe in a heavy-metal (particularly cobalt and copper) contaminated water and soil sample from a tailing dam site in Kitwe in the Zambian Copperbelt. *C. testosteroni,* a member of the β-proteobacteria, is commonly isolated from contaminated soil and water systems, and strains such as T-2, I 2, and TA441 are known particularly for their ability to biodegrade organic aromatics such as arylsufonates (Junker et al. 1997), chloroanilines (Boon et al. 2000), and phenols (Arai et al. 1998) respectively. *Comamonas* strains are also reported to be resistant to toxic metals such as cadmium (Kanazawa et al. 1996).

2 Methods

Sediment core samples were collected from a wetland next to Tailings Dam 25 in Kitwe, Zambia. It is one of the oldest tailings deposits constructed with little environmental protection, leading to easy metal mobilization in aquatic enviornment. Sediment and porewaters were analyzed for near surface sediments to understand metal cycling. Sediments from the same cores were used to isolate bacteria and the bacteria analyzed using TEM and gene sequencing techniques. Baterial isolates were cultured in the lab to further conduct metal resistance assay. Metal tolerance, uptake and accumulation of Co in the isolate was investigated through systmatic experiments.

3 Results and Discussion

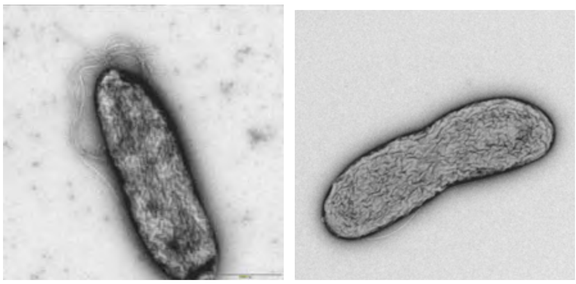

Figure 1 TEM analysis of pure isolate from tailings dam sample. The bacteria have similar crenulated surface characteristics as observed in microscopic examination of other environmental samples.

Optical microscopic analysis of the samples collected at the TDK site showed the presence of diverse morphotypes, including cocci, rods and highly motile spirilla. Closer examination using TEM identified many pseudo-rod shaped bacteria with flagella and a crenulated appearance (Fig. 1). A pure isolate (TDKW), capable of growing under both microaerobic and aerobic conditions, was isolated from liquid cultures inoculated with the environmental sample. Analysis of the 16s rRNA gene sequence indicated that isolate TDKW was a strain of *Comamonas testosteroni*, showing 99% identity with over 35 different strains of *C. testosteroni.*

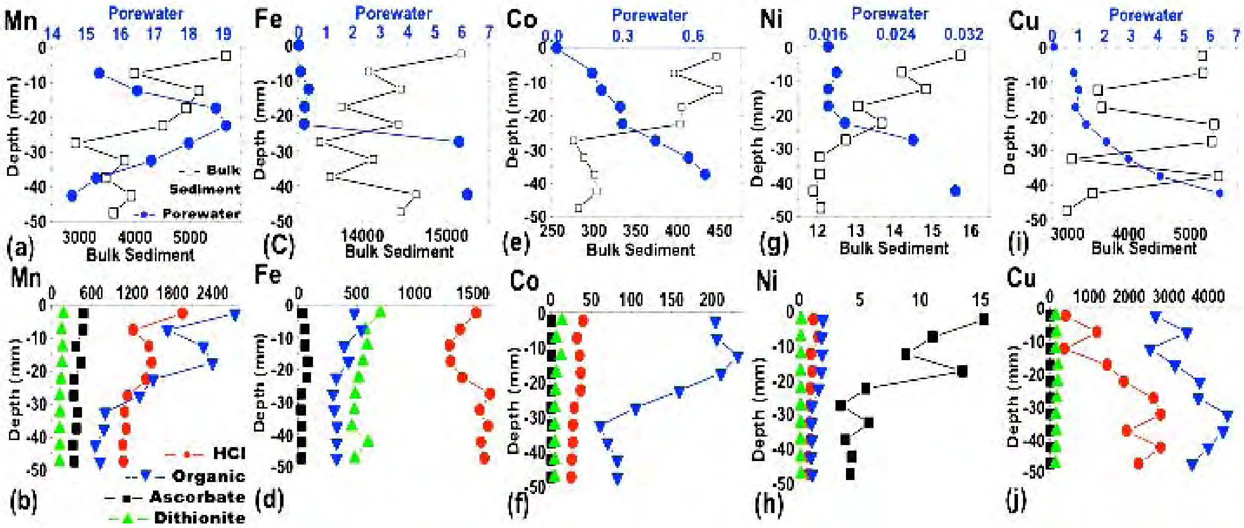

Figure 2. Metal profiles of Mn, Fe, Co, Ni and Cu in a 50 mm deep core of the TDK site. Top row = soluble elements from the porewater and the total bulk sediment concentrations. Bottom row = sequential sediment extracts All concentrations are in ppm.

Selected bioactive trace elements were analyzed in sediment and porewaters of a core from Kitwe site. Analyses showed clear evidence of microbially mediated post-depositional cycling (Fig. 2). Generally the bulk metal concentration in the sediment decreased with depth and a corresponding increase was observed in the porewater trace metal content.

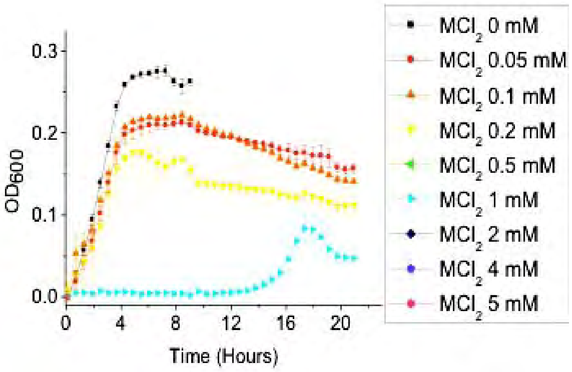

Figure 3. Growth of *C testosteroni* with increasing concentration of Cu. Similare experiments were conducted witth Co, Ni, Fe and Mn.

Growth experiments show bacteria to be well adapted to high concentrations of heavy metals and increasing growth was observed up to 200 μM (e.g., Fig. 3) for all elements except for Fe were growth peaked at 1 mM. Cells grown in cobalt showed a steadily increasing lag time with increasing concentration (3 hrs for the preferential growth conditions of 50–100 μM, and 4, 10, 14 and 17 hrs for 200 μM, 500 μM, 1 mM and 2 mM, respectively). The positive effect of cobalt on cell growth was further investigated in a separate growth experiment. Cells grown in both TBMSM and BM containing 100 μM cobalt (the optimal concentration) were analysed for the presence of cobalt. *C. testosteroni* TDKW cells were found to accumulate cobalt in both media, suggesting intracellular uptake of cobalt. This accumulation was progressive during growth, with a dramatic increase in intracellular cobalt concentrations at the end of the lag phase and throughout the exponential and stationary phases. Uptake experiments for other metals showed, cadmium and zinc were accumulated in similar concentrations to cobalt, iron accumulation was observed (3-fold higher compared to cobalt) and accumulation of copper, nickel and manganese was negligible.

4 Conclusions

During the rainy season in the Zambian Copperbelt (December-April), the volumes of water flowing through the area is 1–2 orders of magnitude higher than in the dry season (Pettersson et al. 2001). This results in increased mobilization of heavy metals from spoil heaps and tailings dams causing contamination of local soil-water systems. Due to the high concentrations of cobalt and other trace metals in this environment, micro organisms might be expected to possess adaptive biological functions. This is shown here for Co, accounting for the substantial positive effect cobalt has on growth and its accumulation in *C. testosteroni* TDKW. The fact that cobalt promotes cell growth and yield is very intriguing and leads to speculation that cobalt could be functionally important for this microbe. It is well known that some metal ions such as Fe and Mn are commonly redox cycled and solubilised by microbes in sediment-water systems (Lovley 2000), but little is known of microbial Co cycling. Cobalt metal redox cycling could be employed by *C. testosteroni* TDKW to benefit cell growth.

Acknowledgements

Michael Coppock, Marla Tuffin, and Lonnie van Zyl contributed to this work. Material in this abstract is extracted from article originally published in Geomicrobiology Journal by the authors. Funding support was provided by NRF, South Africa.

References

Arai et al. (1998). Adaptation of *Comamonas testosteroni* TA441 to utilize phenol: organization and regulation of the genes involved in phenol degradation. Microbiology 144(10): 2895–2903

Boon et al. (2000). Bioaugmentation of activated sludge by an indigenous 3-chloroaniline-degrading *Comamonas testosteroni* strain, I2gfp. Appl Environ Microbiol 66(7): 2906–2913

Junker et al. (1997). Conjugative plasmids and the degradation of arylsulfonates in *Comamonas testosteroni*. Appl Environ Microbiol 63(6): 2403–2410

Kanazawa et al. Isolation of cadmium-resistant bacteria and their resistance mechanisms. Part 1. Isolation of Cd-resistant bacteria from soils contaminated with heavy metals.1996. Soil Sci Plant Nutr (Tokyo) 42(4): 725–730

Kosolapov et al. (2004). Microbial processes of heavy metal removal from carbon-deficient effluents in constructed wetlands. Appl Environ Microbiol 63(6): 2403–2410

Lovley (2000). Editor, Environmental Microbe-Metal Interactions. Washington, DC: American Society of Microbiology.

Nies (1999). Microbial heavy-metal resistance. Appl Microbiol Biotechnol 51(6): 730–750

Nies (2000). Heavy metal-resistant bacteria as extremophiles: molecular physiology and biotechnological use of Ralstonia sp. CH34. Extremophiles 4(2): 77–82

Wood (1987). Biological processes involved in the cycling of elements between soil or sediments and the aqueous environment. Hydrobiologia, 149: 31–42

IGCP/SIDA Project 594, Inaugural Workshop, Kitwe, Zambia, 2011, © Czech Geological Survey, ISBN 978-80-7075-119-0

Risk assessment of gold and uranium mine residue deposits on the Eastern Witwatersrand, South Africa

M. W. Sutton
University of the Witwatersrand, Johannesburg, South Africa & AngloGold Ashanti Limited

I. M. Weiersbye, J. S. Galpin & H. Tutu
University of the Witwatersrand, Johannesburg, South Africa

N. Margalit, R. Stark & D. Heller
Elbit Systems Electro-Optics - Elop, Israel.

Abstract. Elements from gold and uranium mine residue deposits (MRDs) on the Witwatersrand are transported into the surrounding environment through wind and water. The aim of this study was to provide a simple decision-support tool to aid in prioritising MRDs for mitigation and reaching agreement on safe end land uses. We used a numerical rating scheme for a risk assessment, which combined a number of parameters in two separate stages to calculate a risk index. The first stage involved the classification of hazards while the second involved an assessment of receptor vulnerability. Selecting the Ekurhuleni Metropolitan Municipality as a study site, we combined historical aerial photographs with geographical and satellite-based multi-spectral data in a Geographical Information System. Thematic images for five mineral signatures that we considered indicators of different routes of contaminant transport were derived from ASTER sensor data. We selected acid rock drainage and dust as the major hazards and assigned ratings for different classes of MRDs. For the vulnerability assessment, we identified proximity of MRDs to dolomites, watercourses, agricultural land and dwellings as critical. Of the 287 MRDs identified, we classified 50% as probably being of lower-risk; 40% as probably of medium-risk and 10% probably of higher-risk.

Keywords. Acid rock drainage, gold and uranium mining, remote sensing, risk assessment, safe land use, Witwatersrand basin

1 Introduction

Under section 24 of the Constitution of South Africa Act 108 of 1996 (the Constitution), the right to environmental health has been elevated to a basic human right, and since 1998 a series of Acts have been promulgated to prioritize environmental protection. The Mineral and Petroleum Resources Development Act 28 of 2002 (the MPRDA) and its Regulations (GN R527 in Government Gazette 26275 of 23 April 2004) attempt to ensure sustainable development of mineral resources, equitable access to the benefits, better environmental protection, and include provisions for mine closure. A key requirement of the MPRDA is for mining companies to undertake the necessary studies to determine the quantum required for the rehabilitation or management of impacts, and to make sufficient financial provision for these. The MPRDA also attempts to establish an exit route whereby mining companies, which demonstrate an agreed degree of environmental compliance, can then transfer their remaining liabilities to the State or a third party together with sufficient funds to address them. However, if funds are insufficient, the mining company and the directors in their personal capacity remain liable. Thus it is vital that mining companies and directors keep abreast of international trends in order to pro-actively minimize their exposure. Un-answered questions relate largely to end land-uses and restrictions thereon.

Since 1886, hundreds of gold mine residue deposits (MRDs), known as dumps or dams, have been built across the Witwatersrand Basin. Gold deposits on the Witwatersrand Basin also co-occur with uranium-bearing minerals. During the 1950s metallurgical plants were constructed for the extraction of uranium and pyrite from gold residue (i.e. once the gold had been recovered). By the mid-1970s gold recovery processes had improved sufficiently to also allow residual gold from old tailings to be recovered at a profit, and this resulted in dump reprocessing operations and the clearing of soils previously covered by mine dumps.

With the curtailing of mining activities and clearing of land previously covered by mine dumps, there comes a demand to use this land for residential, agricultural or industrial purposes. However, mining companies historically employed little pollution control (e.g. no covers, linings or effluent treatment prior to discharge) and residue material was used for road building, construction and fill purposes. Furthermore, the chemical influence of residue deposits has been identified many kilometres downstream from what is thought to be the original point sources (Tutu et al., 2008).

The East Rand (Ekurhuleni Metropolitan Municipality, EMM) was selected as our study site. It is the largest industrial area in South Africa and a century ago was the world's largest producer of gold. However, gold mining now contributes only about 2% to its economy.

2 Study aim and objectives

2.1 Study aim

The aim of this study was to provide a gold mining company (AngloGold Ashanti Ltd), the provincial environmental regulator (Gauteng Department of Agriculture, Conservation and Environment - GDACE) and the local Municipality (Ekurhuleni Metropolitan

Municipality - EMM) with a simple decision-support tool, based on risk assessment, to aid in prioritising MRDs for mitigation and reaching agreement on safe and sustainable end land uses.

To achieve the aim, one of our objectives was to determine which remotely-sensed minerals are the most conservative signatures of different types of MRD (rock, sand or slime), emission pathways and land contamination. The Highveld is highly seasonal, with summer rainfall of 500-750mm and annual evapotranspiration (ET) of >2.5 times mean annual precipitation (MAP), which suggests that efflorescence minerals could be used to identify sources of acid generation and off-site impacts.

3 Method

3.1 Risk assessment

We used a numerical rating scheme for a risk assessment, which combined a number of parameters in two separate stages to calculate a risk index. The first stage involved the classification of hazards associated with MRDs while the second involved an assessment of receptor vulnerability.

3.2 Geographic information system

A Geographical Information System (GIS) was constructed using historical aerial photographs (1938, 1964 and 2003), spatial data (i.e. geology, hydrology, land use and MRD geotechnical features) and semi-quantitative thematic images of eight minerals, which we considered potential indicators of MRD emissions by different transport routes under Highveld conditions. MRDs were georeferenced and categorised in terms of underlying geology, basic geotechnical properties, historical spillages and historical pollution control measures to determine any relationship between mine residue deposit category and spatial extent of the impact on the surrounding environment. We used the historical photographs to identify tailings spillages and historical pollution control measures, and identified these minerals as potential indicators of either physically-transported tailings material or water-borne contaminants (although all also occur naturally).

We identified and classified MRDs according to type, status or footprint type, and then subjectively identified the hazards to land use based on a scientific literature survey. We selected acid rock drainage and dust as the major hazards and then utilised the findings expressed in the literature survey to assign ratings for the different classes of MRDs.

3.3 Mineral signatures

We chose two primary minerals characteristic of gold-bearing tailings (pyrophyllite and chlorite), three secondary sulphate minerals with distinct precipitation chemistry and solubility (copiapite, jarosite and gypsum), two contrasting iron oxides (goethite and haematite), and a potential surrogate signature for uranium-bearing residues ('mincrust', Cukrowska et al., 2006; Margalit et al., 2009). Thematic images were compiled for pyrophyllite, chlorite, copiapite, jarosite and mincrust from data acquired for the East and Central Rand polygon over two years (2002 and 2003) in two seasons (Austral spring and summer) by the TERRA satellite's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, and for all eight minerals from hyper-spectral data, acquired for the West to East Rand airborne transects in August 2005 with a push-broom AISA-ES sensor. The airborne transects were replicated at 10,000 and 25,000 fagl in order to assess the influence of altitude on mineral detection and spatial extent. Ground-based data acquisition using an analytical spectral device (ASD) was undertaken simultaneously with sampling for chemical analysis during the airborne campaign and was conducted retrospectively for the ASTER imagery. The normalised difference vegetation index (NDVI) was derived from both the ASTER and hyper-spectral data, and was used to identify any masking effect of active vegetation.

Regression analysis was used to test agreements between ASTER or airborne data, mineral spectra from the USGS spectral library, and ground-truth data. Statistical significance was taken at the 5% level, with the Bonferoni adjustment used for multiple comparison tests. Seasonal impacts on mineral detection by ASTER were assessed using Friedman ANOVA and Wilcoxon matched pairs tests to examine differences in the spatial extent of minerals, and McNemar tests for differences in the probability of detecting minerals. Associations between detected minerals and features (i.e. type of mine residue, spillage, land-uses and vegetation cover) were tested using chi-square (X^2) contingency tables with standardised (Pearson) residuals and odds ratios used to examine the lack of independence.

4 Results and Discussion

4.1 Mineral signatures

Overall, chlorite was found to be an unreliable indicator, whereas mincrust, jarosite, pyrophyllite and copiapite were reliably associated with mine residues, in that order, with mincrust the least masked by active vegetation. The most extensive detection of these four minerals was after a few dry days following the first spring rains. Distinct zonation of copiapite and jarosite, corresponding to substrate pH, was clearly visible on MRDs, whereas mincrust and pyrophyllite distributions were independent of pH. Gypsum was strongly associated with ARD-contaminated evaporative sinks on dolomitic substrata, including areas being irrigated with gypsiferous water. The iron oxides were associated with bare soils but could only be discriminated between at low altitude, with goethite detected at higher concentrations on ARD-contaminated than on uncontaminated soils. Pyrophyllite and copiapite were enriched on industrial and business lands, and appeared to be associated with tailings dust capture by large roofs; and, in the case of copiapite, oxidation. Jarosite and mincrust were reliable indicators of mining residues.

Jarosite was consistently detected on MRDs and on some soils that had previously supported MRDs (`footprints’). Mincrust was consistently detected on both the former and also on spillages, reef weathering deposits in drainage lines, wetlands, waste rock used in construction, sand in golf course bunkers and old irrigated lands, which had been recently developed. These sites contained uranium in localised surface deposits or crusts at concentrations of 50 to 800 ppm. Mincrust was detected on some irrigated croplands with an odds ratio of 10 to 36 times greater than for rain-fed croplands, which suggests an aqueous/evaporative pathway from contaminated sources of irrigation. In conclusion, although a combination of pyrophyllite, copiapite, jarosite, mincrust, gypsum and goethite can be used to screen entire gold and uranium mining districts on the Highveld for mine residues and associated contamination, we found that jarosite was the most continuous signature of MRDs, whereas mincrust was a consistent surrogate indicator of off-site contamination on diverse substrata.

4.2 Receptor vulnerability

For the assessment on receptor vulnerability (Sutton et al., 2006; 2008), we found that many gold slimes residue deposits are situated in drainage lines or old wetlands and have suffered side wall failures, and that this has resulted in extensive historical spillages on land and into watercourses. Pollution control measures such as paddocks were found to have been constructed after spillages had occurred, and therefore their effectiveness is difficult to gauge. Mineral signatures that we considered typical of gold residue deposits and AMD, such as jarosite and uranium-bearing minerals, were also associated with reef outcrops and with some irrigated lands. The residue deposits were classified further using the GDACE C-Plan 2 and EMM Spatial Plan, in terms of surrounding land-use, housing density, geology (particularly dolomites), soils, distance from water-courses, vegetation and ecosystem type since the nature of the receiving environment appears to have a major influence on the extent and impact of emissions (i.e. via transmission, attenuation or buffering).

4.3 Risk assessment

Of the 287 MRDs identified, we classified 50% as probably being of lower-risk; 40% as probably of medium-risk; 10% probably of higher-risk and 0% as probably of very high risk. All 30 of the higher-risk sites were slimes dams. The results of this assessment will support the selection of sites for more quantitative assessments; either for verifying the findings (by selecting a subset of sites from each category) or for designing mitigation or remedial measures for the higher-risk sites. Further assessment of mincrust mineralogy, speciation chemistry and stable isotope ratios is recommended.

5 Conclusion

The extent of gold and uranium mining, and heterogeneity of substrata and land uses, means that decision-making needs to be based on risk assessment at both the regional and site-specific scale. From a regional perspective, using remote sensing, GIS and a literature review, this assessment has identified 30 of the 287 MRDs (i.e. 10%) as being of higher risk, thereby enabling prioritisation of resources. Dwellings and agriculture, in particular irrigated agriculture, were identified as vulnerable end land uses for MRD footprints or areas within the zone of influence of MRDs. Thus, when determining land uses and setting closure objectives in metal mining regions, residual and latent impacts such as bioaccumulation and impaired ecosystem functioning need to be considered. Through so doing, future harm and liabilities can be avoided. Towards this we recommend the restriction of certain land uses on MRDs, footprints and polluted areas, and the implementation of buffer zones, pending quantitative environmental risk assessments.

Acknowledgements

This research formed part of M.W. Sutton’s MSc studies at the University of the Witwatersrand, Johannesburg and was supported by AngloGold Ashanti Ltd and the THRIP programme of the Department of Trade & Industry of South Africa. We are grateful to the Council for Geoscience, the Government Surveyor General, the SADF, the DME, the EMM, GDACE and the University of Maryland, U.S.A. for making data freely available (or at minimal cost). El-Op and Bar-Kal Systems Engineering (Israel) generously provided the thematic ASTER imagery to our specifications. Access to land for ground-truthing purposes was provided by AngloGold Ashanti Ltd, DRD South Africa, Crown Gold Recoveries, Harmony, the National Department of Agriculture and various private land-owners.

References

Annegarn, H.J., Surridge, A.D., Hlapolosa, H.S.P., Swanepoel, D.J. DE V. and Horne, A.R., (1991). A review of 10 years of environmental dust monitoring at crown mines, *Journal of the Mine Ventilation Society of South Africa*, pp. 46–50.

Cukrowska, E.M., Tutu, H. and Weiersbye I.M., (2006). Assessment of chemical composition and potential mobility of elements in water, sediments and evaporated salts of representative mine evaporative pans. In: Z. Agioutantis and K. Komnitsas (eds), *AMIREG 2006: Advances in Mineral Resources Management and Environmental Geotechnology,* Athens, pp. 567-572.

Margalit, N., Weiersbye, I.M., Beyth, M., Zur, Y. and Stark, R., (2009). Mapping of uranium-bearing materials using hyperspectral remote sensing techniques in the Witwatersrand Basin, South Africa. 6th EARSeL SIG IS Workshop, Israel, March 2009.

Naicker K, Cukrowska E and McCarthy TS, (2003). Acid mine drainage arising from gold mining activity in Johannesburg, South and environs. *Journal of Environmental Pollution*. 122. 29-40

Sutton, M.W. (2009). Unpublished MSc project, School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Johannesburg, South Africa.

Sutton, M.W. and Weiersbye, I.M. (2007). South African legislation pertinent to gold mine closure and residual risk. In: A.B. Fourie, M. Tibbett and J. Wiertz (eds). Proceedings of the 2nd International Seminar on Mine Closure, Santiago, ISBN 978-0-9804185-0-7, pp. 89–102.

Sutton, M.W. and Weiersbye, I.M. (2008). Risk assessment of gold and uranium mine residue deposits on the Eastern Witwatersrand Basin, South Africa. In: A.B. Fourie, M. Tibbett, I.M. Weiersbye and P.J. Dye (eds). Proceedings of the 3rd International Seminar on Mine Closure, Johannesburg, South Africa, pp. 363-374.

Sutton, M.W., Weiersbye, I.M., Galpin, J.S and Heller, D., (2006). A GIS-based history of gold mine residue deposits and risk assessment of post-mining land uses on the Witwatersrand Basin, South Africa. In: A. B. Fourie and M. Tibbett (eds), *Mine Closure 2006*, Perth, pp. 667–678.

Tutu, H., McCarthy, T.S. and Cukrowska, E.M., (2008). The chemical characteristics of acid mine drainage with particular reference to sources, distribution and remediation: the Witwatersrand basin, South Africa as a case study, *Applied Geochemistry 23: 3666-3684*.

Weiersbye, I.M., Margalit, N., Feingersh, T., Revivo, G., Stark, R., Zur, Y., Heller, D., Braun, O. and Cukrowska, E.M., (2006). Use of airborne hyper-spectral remote sensing (HSRS) to focus remediation and monitor vegetation processes on gold mining landscapes in South Africa. In: A.B. Fourie and M. Tibbett (eds), *Mine Closure 2006,* Perth, pp. 601-611.

.

Chemistry of surface waters of Kitwe region – preliminary results

S. Wołkowicz, P. Dobek, & Z. Kowalski
Polish Geological Institute-National Research Institute, 4 Rakowiecka str., 00-975 Warsaw, Poland, stanislaw.wolkowicz@pgi.gov.pl

I. Nyambe & M. Chirwa
University of Zambia, P.O. Box 32379, Lusaka, Zambia, inyambe@unza.zm

Abstract. Within the project "Polish aid" funded by the Ministry of Foreign Affairs, Republic of Poland sampling of surface water was carried out in the area of Kitwe (Copperbelt, Zambia). 52 samples of water from the Kafue River and its tributaries were collected. The PGI-NRI Laboratory in Warsaw performed analysis of B, Ba, Ca, Cr, Fe, K, Mg, Mn, Na, P, SiO_2, Sr, Ti, Zn by ICP-AES and determination of Ag, Al, As, Cd , Cl, Co, Cu, Li, Mo, Ni, Pb, Rb, Sb, Ti and U by ICP-MS. Enrichment of the water in few elements (calcium, cobalt, copper, iron) is observed, but the source is mosltly natural geochemical background from geology and mineralization. High concentration of phosphorus is also observed (Wusakile and Kitwe streams). However it is probably related to of discharge of local communal sewage.

Keywords. Polish aid project, surface water contamination, Copperbelt, Zambia

1 Introduction

The copper mining and smelting activities in the Copperbelt Province in Zambia may have a significant impact of water and soil systems and in consequently on human health. The main objective of the bilateral cooperation between the PGI-NRI in Poland and the UNZA in Zambia was a testing case study on the effects of mining and extraction processes on the environment. The subject of this study was to determine the contents of individual metals and metalloids in the environment of surface water and groundwater, aquatic and alluvial sediments, in relation to regional geology (geochemical background) and the distribution of metals from mining activity zones. Water, sediment and soil quality in Copperbel region has been monitored since few years by the Czech, University of Zambia and the Zambian Geological Survey. Polish research team focused on developing a comprehensive methodology for collecting environmental samples along the different types of aquatic environments, as well as presentation and teaching a young team of scientists from the Zambian partner. The methodology used during the field work has been repeatedly tested during the Polish research and therefore applies well to the conditions of the mining activities in the Copperbelt Province.

Polish - Zambian partnership studies are one of the projects that provide information about the environment and identified threats. The responsibility of scientists and politicians in this regard, lies in providing complete information about the state of the environment, the creation of comprehensive tools and legislation to assess and protect the natural resources for creating a balance between environmental protection, aspirations and objectives of the local community and the rapid growth of the mining industry.

2 Methodology

Water samples were collected in the available places in a way as regular as possible to cover a designated area of research. The total number of surface water sampling sites ware 52. Samples were collected from rivers (Kafue, Mwambashi), streams (Kalulushi, Chibuluma, Wusakile, Lukashi, Musakashi) canals and ponds (Mindolo mine area). Water samples were filtered on site using 0,45 μm Millipore filters and acidized with nitric acid in 30 ml bottles. The bottles were also marked with numbers and transferred to the Polish laboratory within 7 days. Specific electrical conductivity (EC), acidity (pH), oxygen (O_2) and electric potential (mV) of water were measured on site. All the sampling sites were marked at topographic maps and location were defined with GPS system. For database safety reasons, all the field data were also noted on special sampling cards.

Chemical analyses were carried out at the Central Chemical Laboratory of the Polish Geological Institute – National Research Institute in Warsaw. Contents of B, Ba, Ca, Cr, Fe, K, Mg, Mn, Na, P, SiO_2, Sr, Ti and Zn in samples were determined by ICP-AES method. Determination of Ag, Al, As, Cd, Cl, Co, Cu, Li, Mo, Ni, Pb, Rb, Sb, Ti and U were analysed using an ICP-MS method.

3. Preliminary results

This paper presents laboratory results obtained for the surface water samples, taken from the vicinity of Kitwe Town. Analyses of water samples show that surface water of surrounding area of Kitwe Town is not polluted by a set of characteristic elements for mining waters, which might have been expected in the Copperbelt region. Enrichment of the water in few elements (calcium, cobalt, copper, iron) is observed, but the source is to a great part natural geochemical background from geology and mineralization. High concentration of phosphorus is also observed (Wusakile and Kitwe streams), however it is probably related to of discharge of local communal sewage.

Statistical data base of measured elements of surface water (Copperbelt region) in relation to the Polish, German and UE legal regulations is shown in Table 1.

A broader analysis of the results (also with other types of samples) is cited under development and will be published at a later date.

Acknowledgements

Studies are realize on the frame of Polish-aid Project “Development of Research Centre in the Directorate of Research and Graduate studies, UNZA through human resources and capacity building by Polish Geological Institute – National Research Institute” (no 282/2011/PR/2011), financed by Ministry of Foreign Affairs of Poland.

Table 1. Statistical data of measured elements of surface water (Copperbelt region) in relation to the Polish, German and UE legal regulations

PARAMETER	NAME	Statistical parameters of chemical elements of water, Copperbelt area		UNIT	Surface water quality guidelines of Poland for I Class (very good water quality)	EU Directive 1998/83/EC DRINKING WATER	EU Directive 2003/40/EC MINERAL WATER	EU Directive 2009/54/EC NATURAL MINERAL WATER		German limits for drinking water (2001)	German limits for mineral water (2008)
		min.	max.								
Ag	Silver	<0.05	<0.05	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Al	Aluminium	1.58	63.56	micro g/L	100	200 (guide value)	n.d.	-	-	200	-
As	Arsenic	<2	3,97	micro g/L	10	10	10	-	-	10	10
B	Boron	<10	60	micro g/L	500	1000	under evaluation	-	-	1000	-
Ba	Barium	0.02	0.24	mg/L	0,1	n.d.	1	-	-	-	1
Be	Beryllium	<0.05	0.05	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Ca	Calcium	1.22	632.78	mg/L	50	n.d.	n.d.	>150	-	-	-
Cd	Cadmium	<0.05	0.19	micro g/L	0,5	5	3	-	-	5	3
Co	Cobalt	<0.05	682.56	micro g/L	20	n.d.	n.d.	-	-	-	-
Cr	Chomium	0	10	micro g/L	50	50	50	-	-	50	50
Cu	Copper	0.85	122.46	micro g/L	n.d.	2000	1000	-	-	2000	1000
Fe	Iron	<10	4310	micro g/L	100	200 (guide value)	n.d.	-	-	-	-
K	Potassium	0.50	86.71	mg/L	n.d.	n.d.	n.d.	-	-	-	-
Li	Lithium	0.29	161.56	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Mg	Magnesium	0.67	142.16	mg/L	25	n.d.	n.d.	>50	-	-	-
Mn	Manganese	<0.5	5.50	mg/L	0,05	50 (guide value)	0,5	-	-	50	500
Mo	Molybdenum	<0.05	83.31	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Na	Sodium	1.74	84.37	mg/L	n.d.	200 (guide value)	n.d.	>200	<20	-	-
Ni	Nickel	<0.50	48.82	micro g/L	10	20 (guide value)	20	-	-	20	20
P	Phosphorus	<50	2910	micro g/L	200	n.d.	n.d.	-	-	-	-

Table 1 (cont). Statistical data of measured elements of surface water (Copperbelt region) in relation to the Polish, German and UE legal regulations

PARAMETER	NAME	Statistical parameters of chemical elements of water, Copperbelt area		UNIT	Surface water quality guidelines of Poland for I Class (very good water quality)	EU Directive 1998/83/EC DRINKING WATER	EU Directive 2003/40/EC MINERAL WATER	EU Directive 2009/54/EC NATURAL MINERAL WATER		German limits for drinking water (2001)	German limits for mineral water (2008)
		min.	max.								
Pb	Lead	<0.05	0.28	micro g/L	10	10	10	-	-	25 (10 from 2013)	10
Sb	Antimony	<0.05	0.73	micro g/L	n.d.	5	5	-	-	5	5
Se	Selenium	<2	20.19	micro g/L	n.d.	10	10	-	-	10	10
Si	Silicon	7.13	21.95	mg/L	n.d.	n.d.	n.d.	-	-	-	-
Sn	Tin	<0.50	1.13	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Sr	Strontium	0.01	4.24	mg/L	n.d.	n.d.	n.d.	-	-	-	-
Ti	Titatnium	<2	<2	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Tl	Thallium	<0.05	0.17	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
U	Uranium	<0.05	50.57	micro g/L	n.d.	n.d.	n.d.	-	-	10	2
V	Vanadium	<1	1.38	micro g/L	n.d.	n.d.	n.d.	-	-	-	-
Zn	Zinc	<3	30	micro g/L	300	n.d.	n.d.	-	-	-	-

MINING AND THE ENVIRONMENT IN AFRICA

***Edited by* Bohdan Kříbek**

Published by the Czech Geological Survey
Prague 2011
Printed in the Czech Geological Survey,
Klárov 3, Prague 1, Czech Republic
03/9 446-410-11
First edition, 71 pages, 70 copies

ISBN 978-80-7075-119-0