

Characterization of contamination of stream sediments and surface water at Otjihase mine, Namibia

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At the Otjihase mine a stratiform massive sulphide mineralization occurs, which is associated with the Matchless Amphibolite Belt. Main ore minerals in the deposit are chalcopyrite and pyrite, with only chalcopyrite being of economic importance. The pyrite dumped in the tailings dump generates acid mine drainage. The aim of the study was to investigate the effects of mining and ore processing on the environment. This was achieved by detailed geochemical investigation of the tailings impoundment, stream sediments, soil and water samples. The samples were analysed for Cu, Zn, Cd, Pb, As and other metals. The results were then compared to regional background values, as well as international soil and water guidelines to assess potential pollution from the mining activities. It became obvious that mining and processing activities at Otjihase, with subsequent disposal of waste rock and tailings, causes significant contamination of stream sediments and surface water. The river system is characterised by elevated copper, zinc, cobalt and chromium contents in both stream sediments and surface water. The main source of contamination is tailings dump (11 million m³ of material). The seepage from the tailings dump and the pyrite stockpiles are highly acidic (pH2) and saline.

Introduction

The Otjihase mine near Windhoek (Figure 1) is Namibia's most important copper mine (Thompson, A, 2006, pers. com). The stratabound copper mineralization is confined to quartz-muscovite schist of the Upper Proterozoic Kuiseb Formation. The mineralization consists mainly of chalcopyrite and pyrite with minor sphalerite, pyrrhotite and galena. The pyrite is being dumped on the tailings and waste rock dumps, and by oxidation, causes acid mine drainage (AMD). Until now, no investigation of surface and ground water quality has been conducted by the mining company or any

governmental or research institution at Otjihase.

The main objective of this study was to determine the effects of mining and ore processing on the environment. This was achieved by a geochemical investigation of the tailings impoundment, stream sediments, soils and water. The samples were analysed for Cu, Zn, Cd, Pb, As and other metals. The analytical results were then compared with baseline samples, as well as international soil and water guidelines. The field work was done by the Division of Engineering and Environment Geology of the Geological Survey of Namibia and the Technical Co-operation Project between BGR (Germany) and GSN (Namibia).

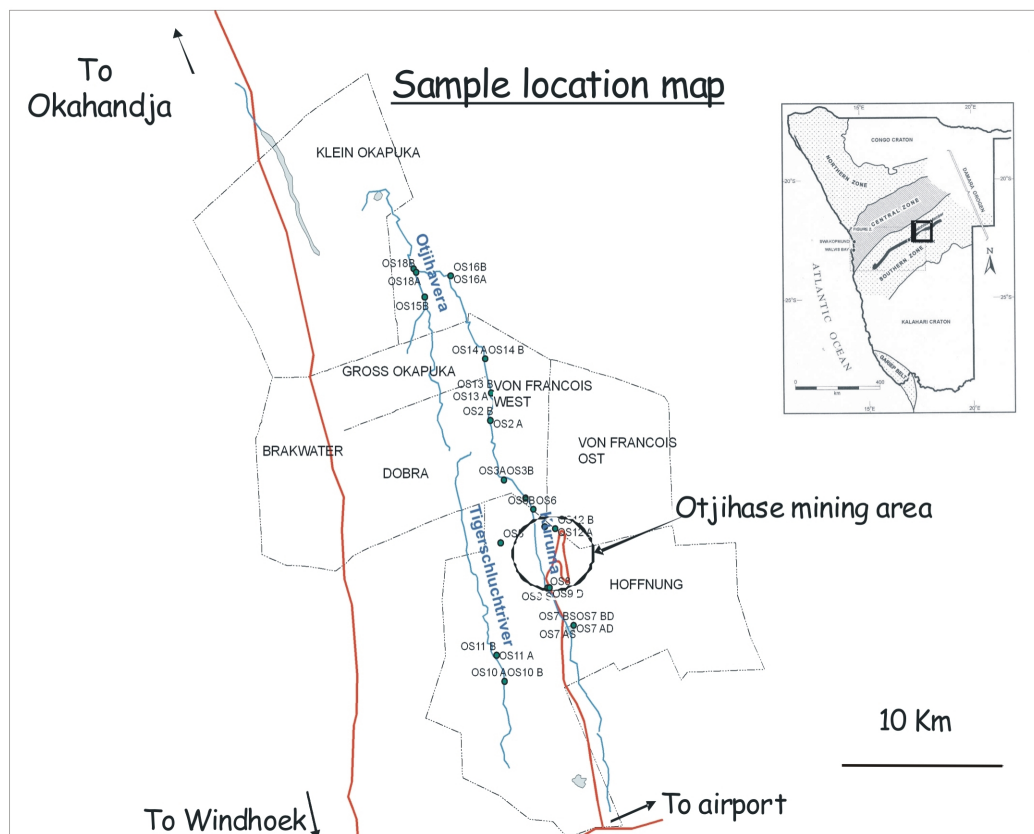


Figure 1: Otjihase study area location map

Geology and mineralisation

The Otjihase deposit (Figure 2) is hosted by the Kuiseb Formation of the Southern Zone of the Damara Orogen; the Kuiseb Formation of the Khomas Subgroup constitutes the upper part of the Swakop Group of the upper

Damara Sequence (Goldberg, 1978). The Otjihase deposit is a stratiform massive cupriferous pyrite deposit (Figure 3), which is associated with the Matchless Amphibolite Belt (MAB). The mineralization is hosted by a quartz-mica-garnet-schist of the Kuiseb Formation and occurs in a strike-limited zone of magnetite quartzite,

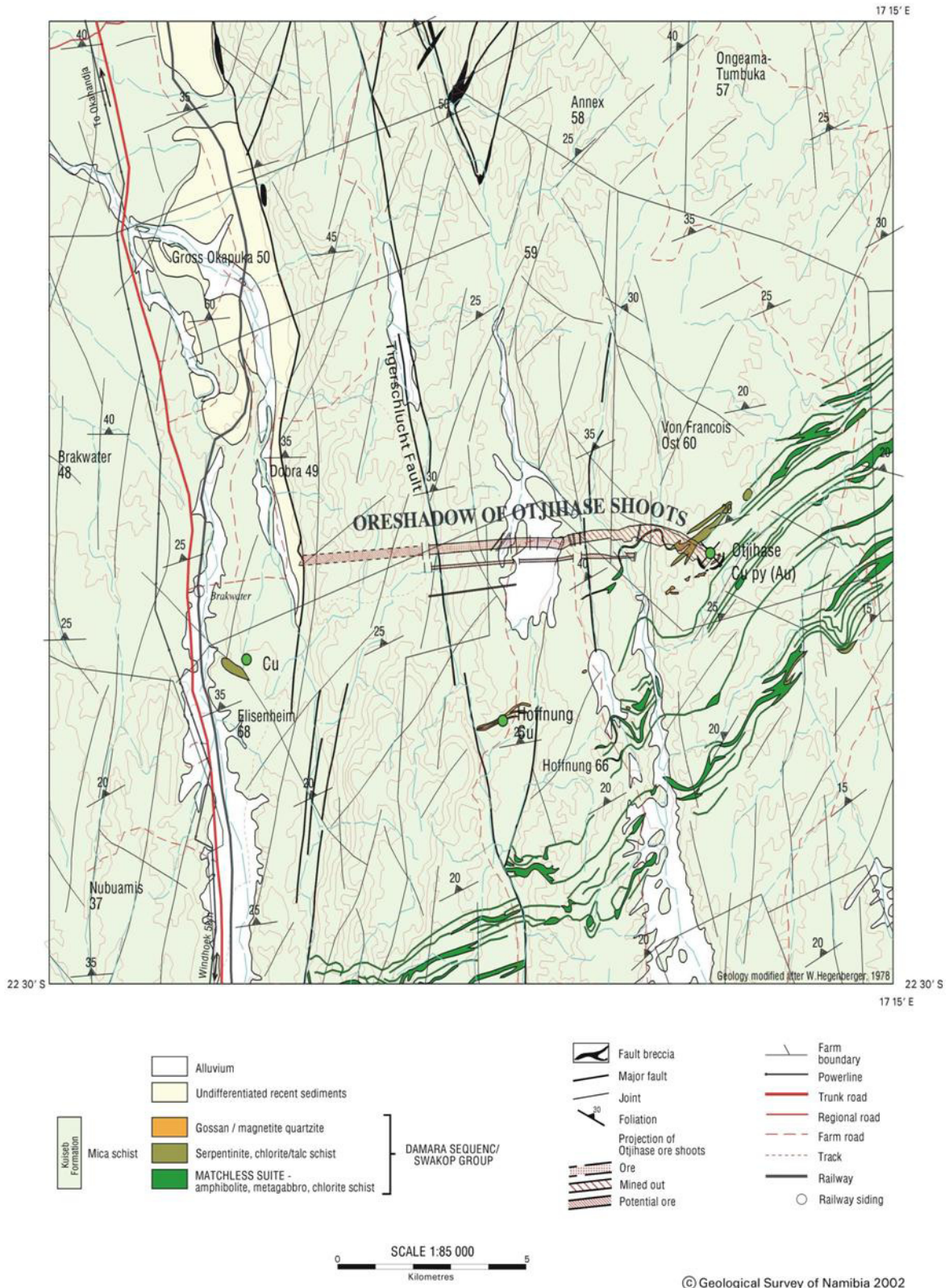


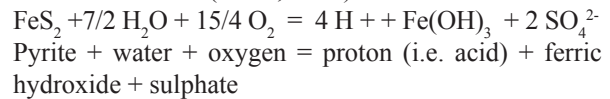
Figure 2: Geological map of Otjihase area (after Geological Survey of Namibia, 2002).

which appears to be stratigraphically conform within the schists (Kennedy, 1978). The ore body is considered to belong to the volcanic-hosted massive sulphide type, similar to the Besshi-type (Knill, 1991). The Otjihase deposit is the largest of the nine known massive sulphide deposits associated with the Matchless Amphibolite Belt (Goldberg, 1976). The Matchless Amphibolite Belt exhibits a surface expression of the Otjihase deposit, which is traceable for about 2 km along strike as a distinctive reddish brown gossan, ferruginous schist and magnetite quartzite. The major sulphide minerals in order of abundance are pyrite, chalcopyrite, sphalerite and minor pyrrhotite and negligible galena (Killick, 1983). Silver is contained in chalcopyrite. Copper is unevenly distributed within the sulphide body and is more concentrated in the main shoot (Kennedy, 1978). At Otjihase, gold occurs as free gold associated with the sulphide minerals, and it is recoverable to a certain extent as a by-product of the main ore minerals pyrite, chalcopyrite and sphalerite (Geological Survey, 1992).

Acid mine drainage (AMD)

AMD originates from mine waste rock, which contains sulphides and occurs in tailings, underground workings and open pit workings. It is primarily a function of the mineralogy of the host rock (Akcil, 2006). AMD is triggered by the availability of water and oxygen. The process is catalyzed by the Fe- and S- bacteria *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans*.

The formation is described in simplified form by the chemical reaction (Akcil, 2006):



At Otjihase mine pyrite is found in the tailings and rock stockpiles, which are the main source of AMD. When exposed to air and water, pyrite oxidizes and gen-

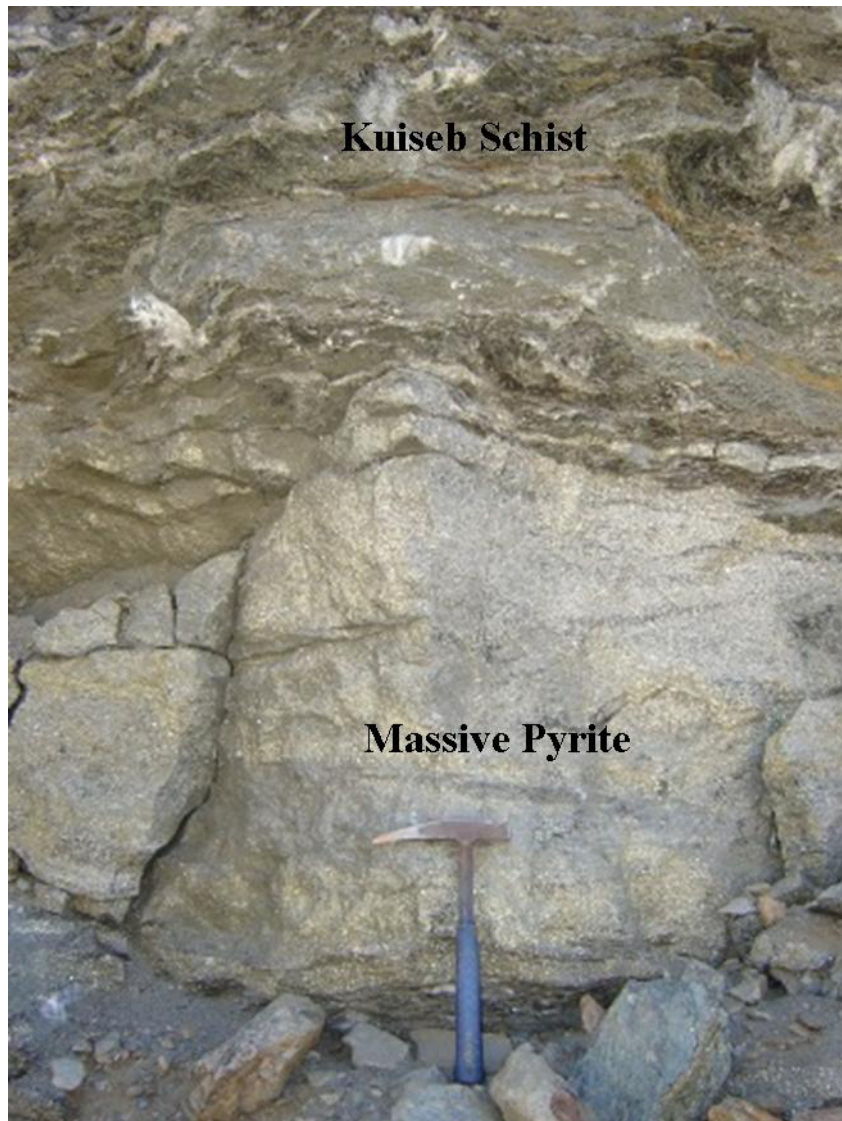


Figure 3: Massive pyrite intercalated with the Kuseib schists as seen in the open pit at Otjihase mine.

erates sulphuric acid. The acid dissolves heavy metals from the dumps and stockpiles. In Otjihase, AMD affected effluents enter a local stream, running alongside the dump. AMD therefore poses a serious threat to the environment and those dependent on it, because it leads to elevated levels of toxic heavy metals and sulphates in stream sediments and in the water.

Sampling methodology

Stream sediments, soils and tailings material

Out of a total of 29 samples, 17 were from stream sediments, 7 samples came from the tailing dumps, and 5 soil samples were collected (Figures 4 and 5). The stream sediment samples were taken along the Kuruma River that drains through the mine property into the neighbouring farms. Samples were taken from different locations in the river bed, mainly adjacent to ponds or running water, but also at completely dry places 5 to 15 km downstream from the mining area. Two baseline samples were taken in the unpolluted Otjihavera river system, where no mineralization occurs (Figure 4). Each stream sediment sample represents composite material taken over a stretch of 5 to 20 m from a traverse perpendicular to the river channel. The tailing and soil samples were taken at surface (0-5 cm) and subsurface (at a depth of 70 to 90 cm) levels from the tailings dump and soil surface. The sub-surface soil samples were used as baseline samples for dust contamination. Efflorescence salts were collected in the drainage channel and the seepage areas of the tailings dump.

Water samples

A total of 14 water samples was collected at accessible water ponds complementing the stream sediment samples (Figure 5) in the river system. Duplicate water samples were collected and stored in polyethylene bottles. One was unfiltered and unacidified and was analysed for anions. The other was filtered through a 0.45µm membrane filter and acidified in the field to a pH <2.0 with 10% HNO₃, and analysed for major cations and trace elements. Samples were stored under cool conditions prior to analysis.

Analytical Methods

Solid samples

For trace element analysis, the stream sediments, tailings and soil samples were analysed using an X-ray fluorescence spectrometer at Rhodes University, South Africa. Five stream sediment and tailings samples, ca. 2g each, were analysed for trace metals at the Council of Geosciences in Pretoria, South Africa, by inductively coupled plasma-mass spectrometry (ICP-MS).

Water samples

The water samples were analysed for trace metals and major cations at Stellenbosch University, South Africa. Methods used include inductively coupled plasma atomic emission spectrometry (ICP-AES) for major ions and inductively coupled plasma-mass spectrometry (ICP-MS) for trace metals.

Polished section

In addition, the mineralogy of tailings and efflorescences was identified with the aid of an X-ray diffractometer (XRD), using a Phillips water cooled diffractometer equipped with a Cu-tube at Rhodes University.

Analytical Results

Stream sediments

Analytical data of stream sediment samples, soils and tailings material are given in Appendix 1 and 2. For sample locations see Figure 4. Stream sediments in the mining area are characterised by high concentrations of Cu (up to 950 ppm) and Zn (up to 950 ppm). Co shows slightly elevated concentrations of 71 ppm and 78 ppm, recorded in stream sediments within the mine property. The concentration of lead is below 127 ppm. Elevated concentrations of Cr were discovered within the mining property with values between 53 and 242 ppm. The concentrations of Cu, Zn, Cr and Co decrease gradually downstream. In contrast, the sediment of the background sample OS120, collected upstream in the Otjihavera River, and thus not affected by the mining activities, was found to contain Cu (14 ppm), Zn (28 ppm), Co (4.9 ppm), Pb (4.6 ppm) and Cr (34 ppm).

Tailings

The tailings material comprises primary gangue minerals such as quartz, sulphide minerals such as pyrite and sphalerite, and oxides like ilmenite and magnetite. The material exhibits the highest concentrations of Cu (up to 7456 ppm) and Zn (up to 1736 ppm), while Co, Cr, V and Zr occur in concentrations >100 ppm. Ni, Th, Pb, Nb and Y have values <100 ppm.

Soils

Soil samples were collected to evaluate the influence of wind in regard to the tailings and the dispersal of the material in the surroundings. Soil samples show low concentrations of Cu (40 ppm) and Zn (61 ppm). The content of Pb (13 ppm), Cr (59 ppm), Co (10 ppm) and Ni (26 ppm) is very low.

Water

Analytical data of the surface water samples are given

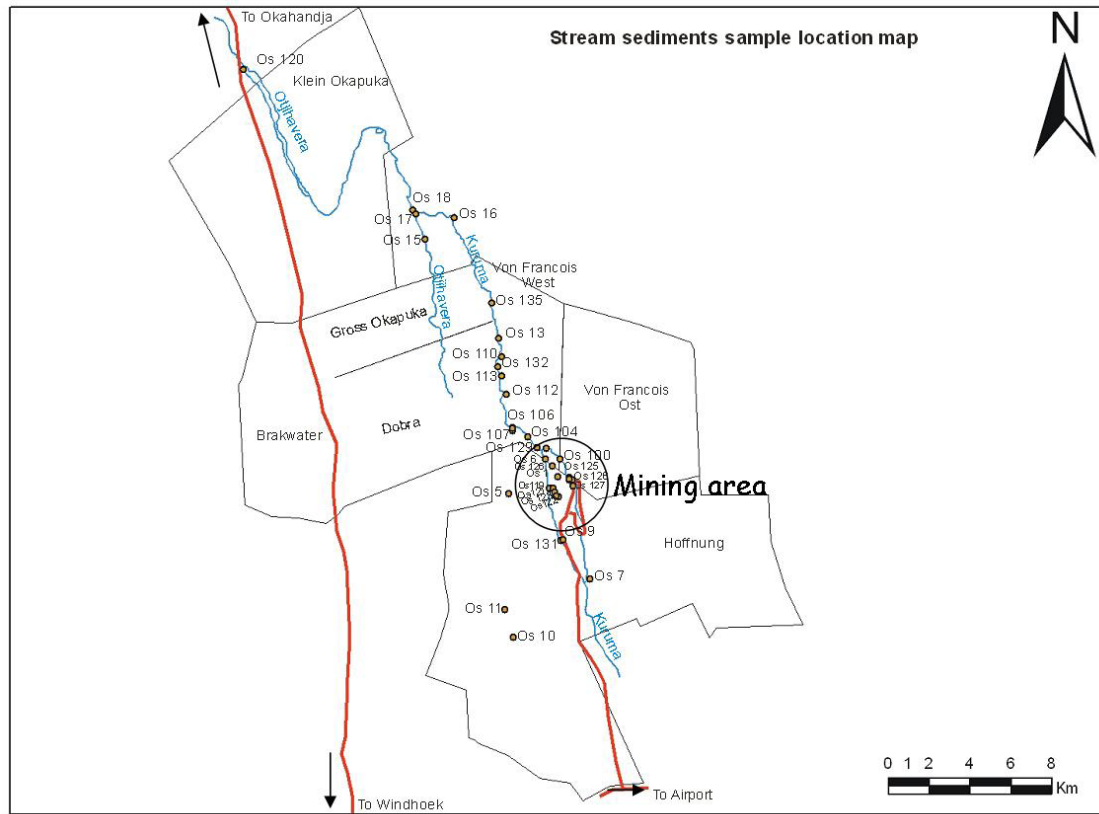


Figure 4: Stream sediments sample location map

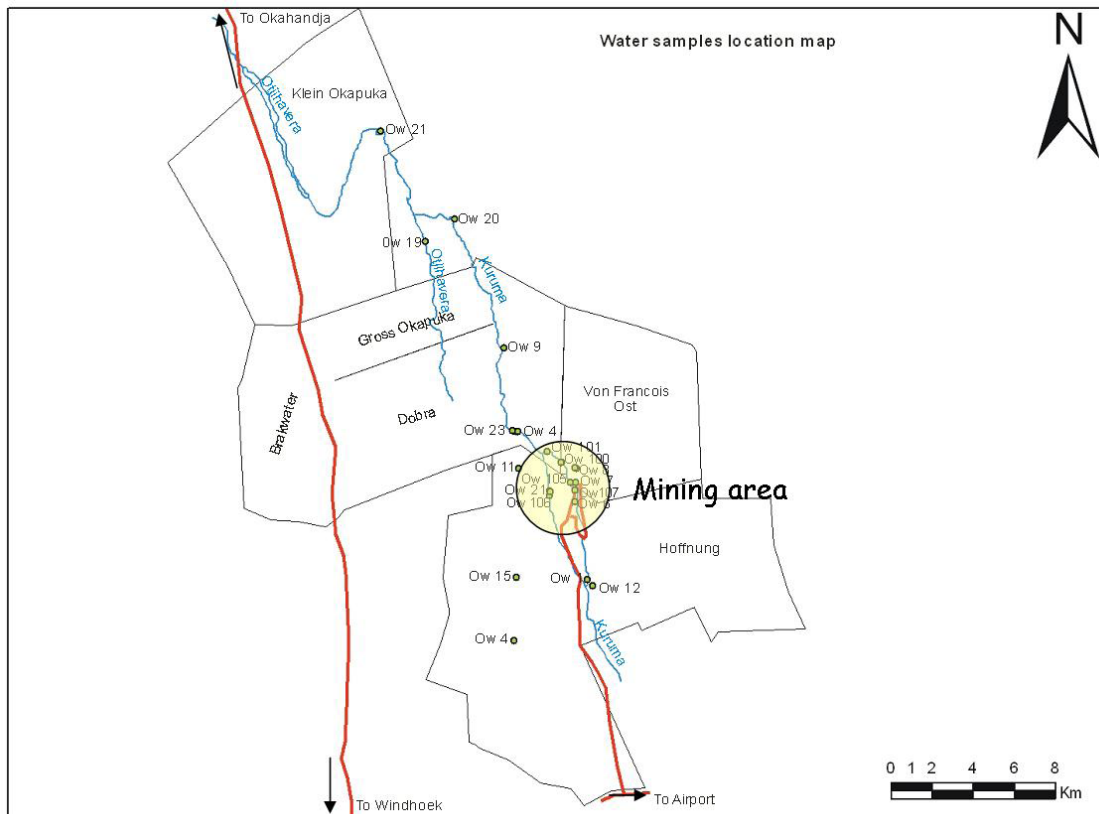


Figure 5: Water samples location map

in Appendix 4 and the sample location map is shown in Figure 5. The seepage water sampled in the mine area revealed generally high electrical conductivity (EC) and low pH. In particular, the pH 3.6 of the seepage from the tailings dam points to acidic conditions. The same sample shows an EC of 12143 $\mu\text{S}/\text{cm}$, and thus is of a saline nature. All water samples of the mine area revealed high averaged concentrations of heavy metals including Cu (13 mg/L), Zn (20 mg/L), Cd (0.07 mg/L) and Fe (147 mg/L), as well as major cations Na (151 mg/L), Ca (436 mg/L) and Mg (320 mg/L). In contrast, water further downstream of the mine workings had a higher pH (8.2), lower EC (390 $\mu\text{S}/\text{cm}$), and lower concentrations of trace metals (Cu 0.67 mg/L, Zn 0.88 mg/L, Cd 0.01 mg/L) and other ions (Fe 0.18 mg/L, Na 63 mg/L, Ca 375 mg/L, Mg 140 mg/L).

Efflorescent salts

XRD-analysis of efflorescent salts revealed gypsum, jarosite and goethite as the major minerals, as well as minor amounts of detritus such as quartz and muscovite. Efflorescent salt samples taken below the tailings dam contain high concentrations of zinc (2045 ppm) and copper (594 ppm; Appendix 5).

Similarly, efflorescences collected near the slimes pipeline tend to exhibit very high copper (4534 ppm) and high zinc (2291 ppm) contents. They also contain traces of Ni, V, Th, Pd, Nb, Zr, Y, Sr, Rb and Ga. Efflorescent salts taken downstream in the Kuruma River show a decrease in Cu and Zn contents to values of 1096 ppm and 984 ppm, respectively (Appendix 5).

Discussion

Stream sediments

Metal concentration trends with distance from the mine tailings dumps are shown in Figures 6 and 7. Stream sediments collected along the river bed are characterised by elevated concentrations of Cu, Zn, Cr and Co, while Pb shows low concentrations. The metal content in sediments changes downstream along the flow path of the Kuruma River as shown in Figures 5 and 6. The concentration of copper, zinc, lead, chromium and cobalt in the sediments decreases downstream with distance from the mine workings, which can be traced over a distance of 13 km. These elements show high enrichment factors of up to 101 for Cu, 23 for Zn, 14 for Pb, 10 for Co and 5 for Cr in stream sediments collected in the mining area (Appendix 6). The concentrations of Co, Zn, Cr and Cu in sediments decrease downstream with distance from the mining area as well. These elements are significantly elevated in stream sediments collected in the mining area when compared to the average background values (Appendix 6). Background samples were used for comparison and evaluation (Appendix 2).

Consequently, the high concentration of Zn, Cu, Co and Cr in the stream sediments taken in or close to the mining area points to two metal sources:

- (1) Natural geochemical footprint of the massive sulphide deposits and sulphide occurrences as well as the associated amphibolite host rock, and

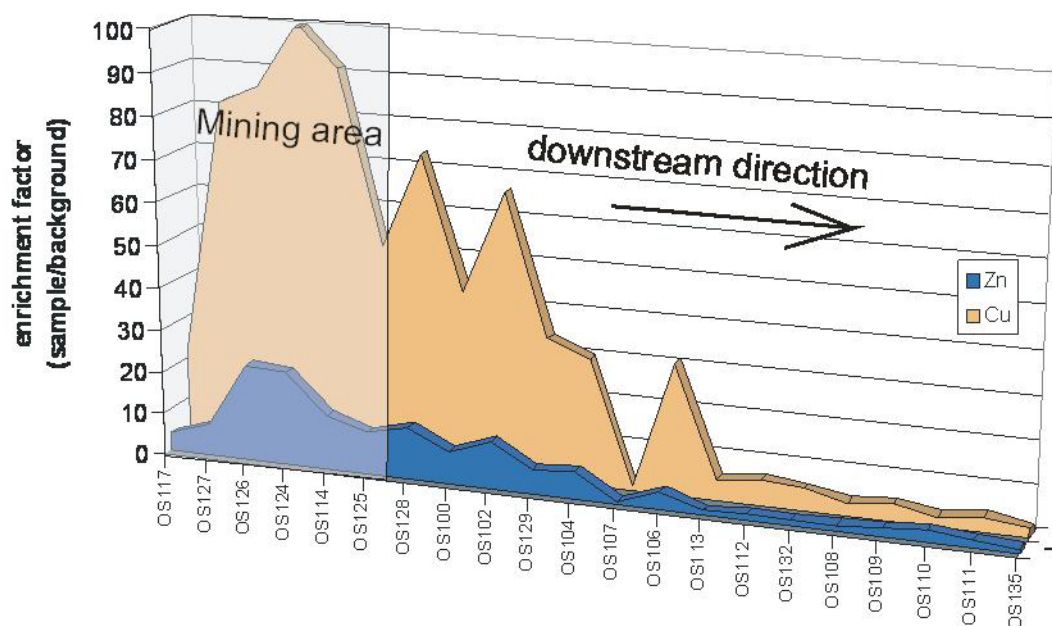


Figure 6: Enrichment factors of copper and zinc in the stream sediments compared to an average reference sample (Appendix 6). The samples to the right of OS128 are plotted with increasing downstream direction from the mining area.

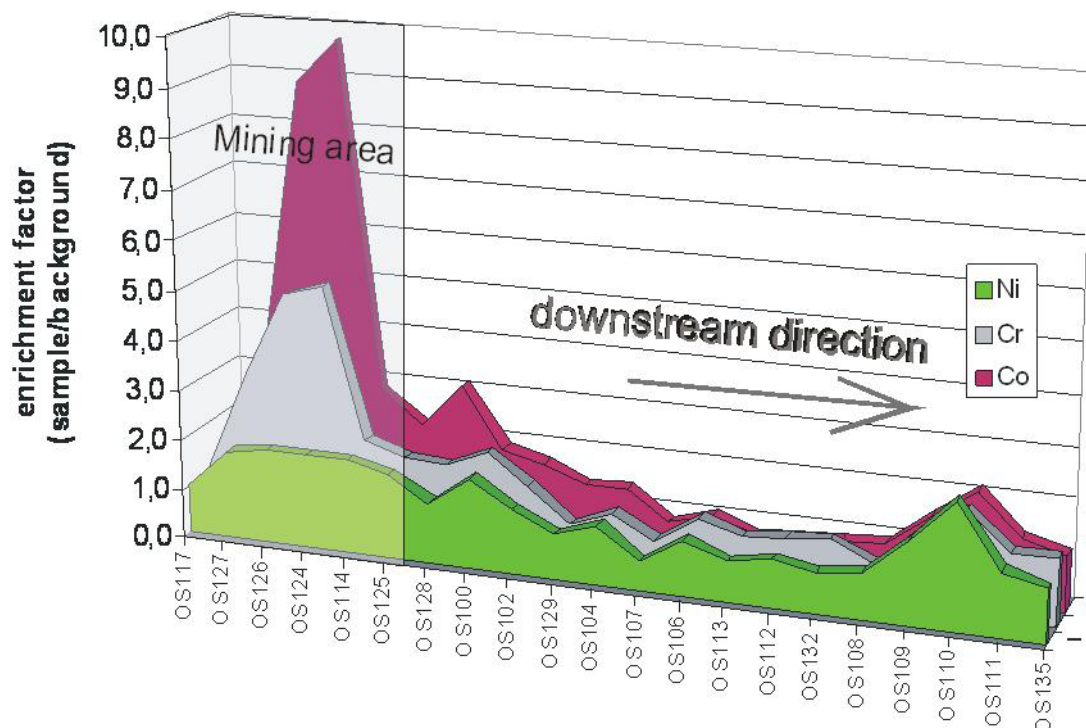


Figure 7: Enrichment factors of nickel, chromium and cobalt in the stream sediments compared to an average background sample (Appendix 6). The samples to the right of OS128 are plotted with increasing downstream distance from the mining area.

- (2) anthropogenic contamination through mining activities.

From the observations at the mining area it can be seen that the anthropogenic factor referred to under (2) predominantly determines the enrichment of the considered heavy metals.

The decrease in metal content downstream can be attributed to

- (1) Dilution due to increased mixing of the mining related particles with sediments derived from unpolluted tributaries,
- (2) loss of mining waste along the channel in accretion deposits, or
- (3) loss via chemical solution (Lewin and Macklin, 1987, Macklin, 1988).

The tailings material shows very high concentrations of Cu and Zn. These elevated concentrations are responsible for those found in the stream sediments.

Soil

For comparison, the German and Canadian soil guidelines (see Appendix 3) are used, in absence of Namibian soil guideline values. Soils in Appendix 2 were found to contain very low concentrations of heavy metals. The contaminants were all below the guideline values, which indicate the natural content of soil. This shows that the soils are not or slightly affected by dust from

the tailings dam.

Water

The surface waters collected in the drainage channel of the Kuruma River, with respect to heavy metal concentrations, show similar geochemical trends as the stream sediments. The metal concentrations of cobalt, zinc and cadmium are elevated in the samples taken in the mine area. The ionic load decreases progressively downstream the Kuruma River. The trend is accompanied by a rapidly increasing pH, from acidic conditions with a minimum pH of 3.3 in the mining area to alkaline conditions with a maximum pH of 8.2 about 2 km downstream. The extremely high concentrations of heavy metals in the seepage from the tailings dump points to the tailings and waste rock dumps as the major source of water contamination (Figure 8).

The acidity of the seepage in the mining area is obviously caused by acid mine drainage. The country rocks of the Kuruma River are mainly muscovite-quartz schists and amphibolites. While the micas have a high retention potential, amphibolite may buffer the acid. The geochemical trends upstream and downstream of the mining area are illustrated in Figure 9.

The high concentrations of zinc found in the contaminated water in the mining area, can be explained by the presence of sphalerite in the tailings. High cadmium contents in the seepage might also be a result of



Figure 8: River on the foot of the tailings dump: Heavily contaminated seepage released into the river system generates efflorescence salts and iron hydroxide precipitation.

sphalerite dissolution. Anomalous Cu values detected in seepage water are associated with the disintegration of chalcopyrite in the tailings, waste rock material and stockpiled pyrite.

Similarly, the elevated concentrations of sodium (Na^+), calcium (Ca^+) and magnesium (Mg^{+2}), sulphate (SO_4^{2-}) occurring in the mining area reflect the high salinity of seepage as a result of acid mine drainage (AMD) (Figure 10). The low pH of 3.6 and 3.9 found in the mine area confirms the presence of AMD (Concas, 2006).

The concentrations of Cu, Cd and Zn in surface water in the mining area exceed the Namibian guideline values for drinking water; thus the water must be classified as group D “unsuitable for human consumption or livestock watering” (Appendix 7, Figure 9).

Heavy metal concentrations decrease rapidly in a downstream direction to values which fall into Group “A” (Cd, Zn) or “B” (Cu) of the Namibian guideline values for drinking water (“excellent to acceptable quality”). Surface waters in the mine workings are polluted according to the analytical evidence. At Otjihase mine and the surrounding area the groundwater level is at 150 and 250 m (DWA, 1997). Hence, the groundwater is only moderately at risk from being polluted.

Efflorescent salts

White and yellow efflorescent salts were observed in the Kuruma drainage channel (Figure 11). XRD analyses of efflorescence salts have shown the presence of

the predominant crystalline phases goethite, gypsum and jarosite, with lesser amounts of thenardite. These salts are present as precipitates from the saline seepage and river water. The abundant occurrence of these sulphate minerals gives evidence for the process of acid mine drainage (AMD) in the Otjihase mining area (Figure 10). During periods of rainfall their dissolution can result in potentially detrimental flushes of acids and metals into the surface water. For example, seasonal flushing of soluble salts from tailings deposits along the Clark Fork River in Montana has been documented as the cause for seasonal fish kills along the river (Plumlee, 1999).

The metal contents in the efflorescent salts were compared with stream sediments from the same sampling location in the Kuruma river bed (Appendix 5). The comparison is reported as enrichment factors of the metal in the salts compared to the sediment. The salts exhibit higher enrichment factors compared to stream sediments. Efflorescent salts distinctly show elevated Cu and Zn contents, while Pb concentrations are below the detection limit. The low concentration of lead reflects a low abundance in the ore and thus, in the tailings material and surface water. In addition, lead sulphate precipitates at very low pH values, so lead will not be mobilized in sulphate dominated surface waters. It rather forms PbSO_4 which is a poorly soluble precipitate in the tailings dump and stays immobile.

In turn, the salts act as the major scavenger for heavy metals, as observed by their high concentrations. Other metals with concentrations above the detection limit

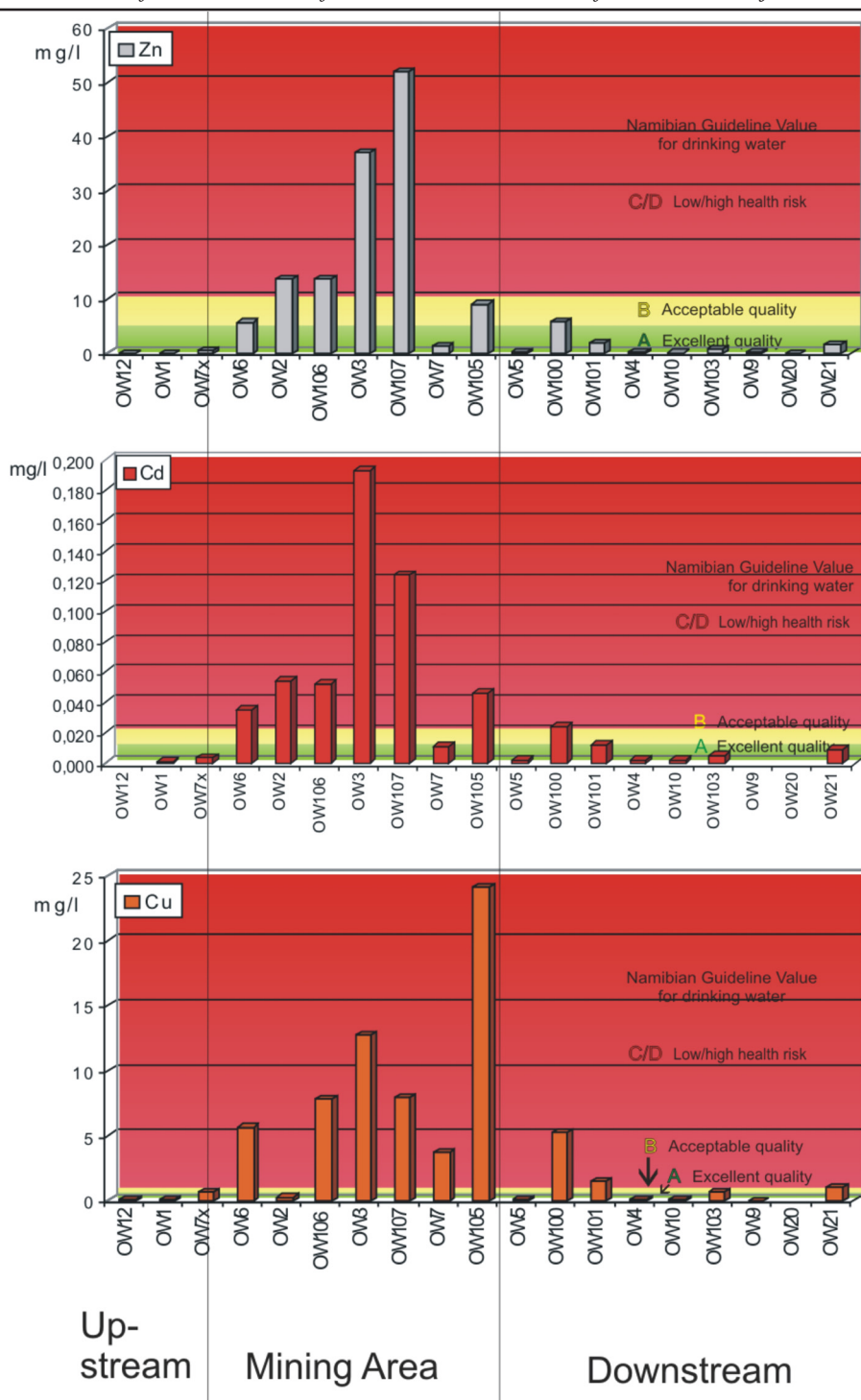


Figure 9: Cu, Zn and Cd histograms showing metal concentrations in water up-and down-stream of the mining area and the Namibian Guideline values for drinking water.

(Ni, Cr, V, Y and Sr) show enrichment factors which are relatively low. While nickel and yttrium are neither relatively enriched in the salts nor in the sediments, vanadium and strontium are relatively depleted in the salts.

Conclusions

Mining and processing have caused an adverse environmental impact on the wider area around Otjihase.

The main sources that have caused severe contamination of stream sediments and surface water with Cu, Zn, Cd, and Cr are the 11 million m3 tailings material disposed of in the tailings dump and the two pyrite stockpiles. Additionally, some contamination seems to derive from spilled tailings material in the mining area.

- Stream sediments blanketing the Kuruma River in the mining area are significantly contaminated with heavy metals such as Cu and Zn, when compared to the average natural background values obtained in the non-

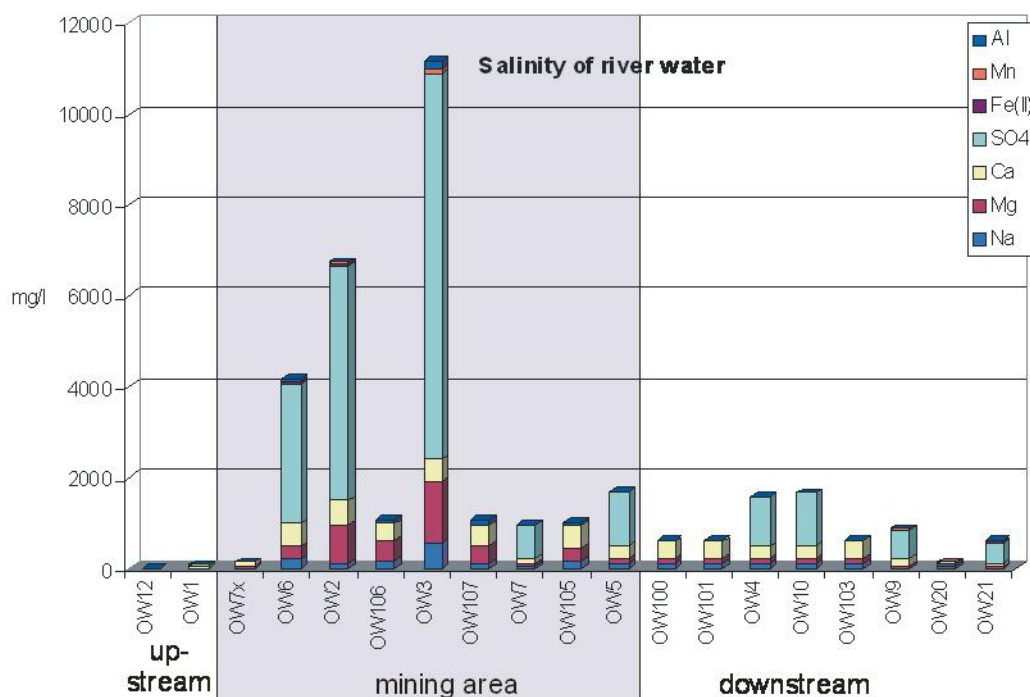


Figure 10: Concentrations of Ca, Mg, Na, Fe and SO₄ in water up-and down-stream of the mining area.

contaminated part of the river. Downstream stream sediments of the Kuruma River show a significant decrease in concentrations of the considered contaminants.

- The soils collected in the wider vicinity of Otjihase mine show heavy metal concentrations close to the background values and are thus not critically contaminated. Therefore wind or dust contamination from the tailings dam is not prominent.

- Surface water from the mining area is highly contaminated with respect to heavy metals and major dissolved ions. Seepage from the tailings dam and the pyrite stockpile is highly acidic (minimum pH 3.3) and saline, with high concentrations of heavy metals. Efflorescent salts with elevated Cu and Zn values precipitated from the seepage and river water. The low pH

and the high metal concentrations of the seepage, as well as the formation of efflorescent salts are typical phenomena for acid mine drainage (AMD), which affects Otjihase mine. Based on the results of this study it is recommended to control and monitor seepage and detritus influx from the tailings dam, as well as seepage from the pyrite stockpiles, to prevent the riverine system from being critically contaminated.

References

- Akcil, A. and Koldas, S. 2006. Acid mine drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production*, **14**, 1139-1145.
- Bell, F.E. 1998. *Environmental Geology*, Blackwell

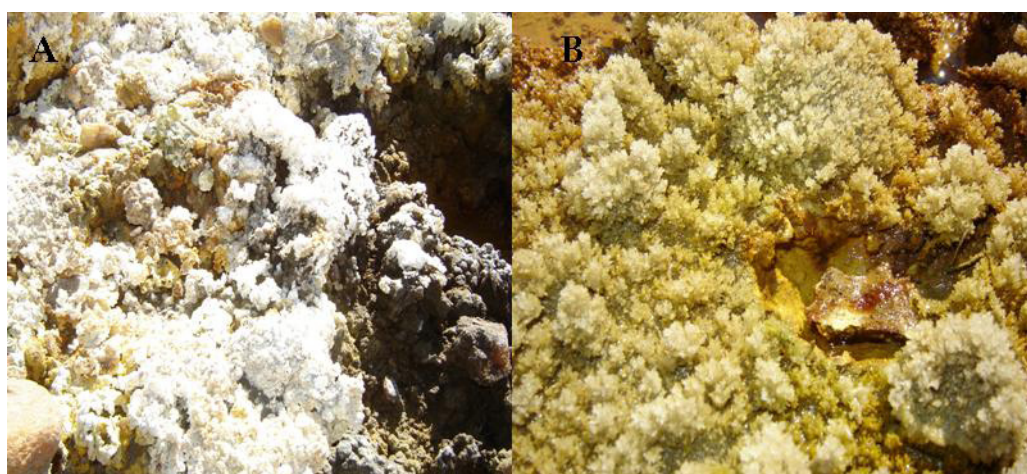


Figure 11: Efflorescent salts in the river channel; A: Idiomorphic crystals of gypsum (width of the picture 12 cm); B: Amorphous crusts (width of the picture 20 cm).

- Science, Great Britain, 594pp.
- Bundesbodenschutz- und Altlastenverordnung, BBod-SchG. 1999. BGBI I S., 1554, 63 pp.
- Concas, A., Arda, C., Cristini, A., Zuddas, P. and Cao, G. 2006. Mobility of heavy metals from the tailings to stream waters in a mining activity contaminated site. *Chemosphere*, **63**, 244-253.
- DWA. 1999. Water Act, 1956 (ACT 54 OF 1956) and its Requirements in terms of Water Supplies for Drinking Water and for waste Water Treatment and Discharge into the Environment. *Department of Water Affairs, Windhoek, Namibia*.
- DWA. 1997. Groundwater potential in the Otjihase Mine Area: Preliminary results. *Department of Water Affairs, Windhoek, Namibia*.
- Goldberg, I. 1976. A preliminary account of the Otjihase copper deposit, South West Africa. *Economic Geology*, **71**, 384-390.
- Kennedy, D.C. 1978. *Geology of the Otjihase copper deposit South West Africa/Namibia*. Unpublished report.
- Killick, A.M. 1983. Sulphide mineralization at Gorob and its genetic relationship to the matchless member. Damara Sequence, SWA/ Namibia. *Spec. Publ. geol. Soc. S. Afr*, **11**, 381-384.
- Knill, M.D. 1991. *The Otjihase massive sulfide deposit: Some petrographical, geochemical, isotopical and structural aspects*. Diplom thesis, ETH Zurich, Switzerland.
- Lewin, J and Macklin, M.G. 1987. The role of fluvial geomorphic processes in the dispersal of heavy metals from mine sites. *Journal of geochemical exploration*, **58**, 101-118.
- Norolstrom, D.K. and Alpers, C.N. 1999. Geochemistry of acid mine waters. In: Plumlee, G. S. and Logsdon, M. J. (Eds): *The environmental geochemistry of mineral deposits. Reviews*. *Economic Geology*, **6A**, 733-760.
- Plumlee, G.S. 1999. The environmental geology of mineral deposits. In: Plumlee, G.S. and Logsdon, M.J. (Eds): *The environmental geochemistry of mineral deposits. Reviews* *Economic Geology*, **6A**, 71-116.

Appendix 1: Coordinates of sample sites of stream sediments, tailings and soil

Sample	Description	Coordinates	
		LAT	LONG
OS100	stream sediment	-22.40952	17.17630
OS102	stream sediment	-22.40486	17.16962
OS104	stream sediment	-22.39972	17.16070
OS106	stream sediment	-22.39582	17.15311
OS110	stream sediment	-22.36479	17.14753
OS111	stream sediment	-22.36479	17.14753
OS112	stream sediment	-22.37302	17.14770
OS113	stream sediment	-22.38127	17.15027
OS114	stream sediment	-22.41810	17.18065
OS117	stream sediment	-22.42250	17.17114
OS120	background stream sediment	-22.23949	17.02286
OS124	stream sediment	-22.41859	17.18072
OS125	stream sediment	-22.41750	17.18074
OS126	stream sediment	-22.41866	17.18227
OS127	stream sediment	-22.42131	17.18253
OS128	stream sediment	-22.41240	17.17270
OS129	stream sediment	-22.40457	17.16494
OS132	stream sediment	-22.36912	17.14590
OS135	stream sediment	-22.34107	17.14274
OS119	Tailings	-22.42238	17.17299
OS121A	Tailings	-22.42396	17.17396
OS121B	Tailings	-22.42396	17.17396
OS122A	Tailings	-22.42614	17.17553
OS122B	Tailings	-22.42614	17.17553
OS123A	Tailings	-22.42578	17.17462
OS123B	Tailings	-22.42578	17.17462
OS107	Soil	-22.39736	17.15343
OS108	Soil	-22.36479	17.14753
OS109	Soil	-22.36479	17.14753
OS130	Soil	-22.44530	17.17705
OS131	Soil	-22.44515	17.17828

Appendix 2: Trace elements analytical data of soil & tailings samples

Sample	Zn	Cu	Ni	Co	Cr	V	Th	Pd	Nb	Zr	Y	Sr	Rb	Ga
	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]
OS100	326.1	802.6	34.6	15	98.6	106.9	6	35.8	10	123.3	21.7	71.7	80.7	14.4
OS102	468.4	1258.9	24.8	13.4	71.4	66.7	3	182	7.3	93.3	30	52.8	44.7	7.5
OS104	265.3	557.2	22.4	10.9	55.3	57.5	2.5	12.7	6.1	78.1	20.3	39.7	40.1	6.7
OS106	174	582.3	20.8	8.1	60.6	60	4.3	16.5	12	103.6	22.8	40.3	33.9	4.4
OS110	110.8	45.3	47.6	17.1	98	127.6	11.3	21.9	16.1	285.2	44.5	126.2	115.9	18.5
OS111	78.9	67.8	24.3	10.4	63.2	63.7	4.1	11.8	10.4	114.6	21.4	41.7	48.8	8.1
OS112	58.5	112.4	18	6.3	51.2	48.1	3.1	12.4	13.4	132.8	16.6	37.5	29.4	6
OS113	40.1	90.6	14.9	6	47.5	41.1	1.8	7.5	8.4	77	10.9	24.8	23.7	4.2
OS114	533.8	1734.6	35.9	22.5	96.8	107.6	6.8	52.8	14.9	227.2	28.9	70	78.2	16.3
OS117	178.6	408.3	18.5	7.3	53.1	74.3	3.7	24.6	8.2	102	14.4	55.1	50.6	10.4
OS120	284	13.5	12.9	4.9	33.9	32.2	2.2	4.6	5.8	73.3	11.5	19.5	26.2	3.6
OS124	926.7	1924.6	35.9	77.7	241.8	196.3	10.6	123.1	10.1	138	23	78.5	97.7	18.1
OS125	411.4	967.4	32.1	17.3	83.8	93.7	5.3	39.1	11.7	157.7	23	77.7	73	14.5
OS126	949.9	1634.7	36.1	70.9	229.5	185.6	8.1	86.7	9.8	157	27	83.9	96.5	19.2
OS127	314.1	1554.3	34	25.4	146.9	181.8	9.1	50.4	13.3	199.2	26.7	108.5	76.3	16.1
OS128	508.4	1390.5	23	24.5	81.9	73.8	8.2	63.2	5.8	107.7	28.3	78.1	53.4	9.1
OS129	248.7	640.2	17.1	10.8	39.9	49.2	2.1	17.3	7.9	84.3	20.5	40.7	34.1	6.2
OS132	52.1	100	15.4	6.6	55.2	56.6	2.9	9.6	25.9	156.9	19.9	28.2	22.2	4.6
OS135	45.8	38.1	19.9	8.7	64.6	54.5	2.4	6.5	12.6	127.9	17	26	32.5	5.5
OS119	1423.8	983.1	24.6	92.4	107.6	114.3	3.5	101.3	6.5	100.5	18	66.2	44.1	11.1
OS121A	1468.5	957.3	26.5	54.1	72.6	81.3	4.8	67.3	8.5	123.2	20.1	67.8	62.8	12.7
OS121B	1785.7	1379.9	22.6	510.2	448.1	249	3.3	84.9	7.6	120	14.8	52.1	29.4	7.1
OS122A	1306.3	2372.8	26.9	257.6	147	110.7	9	55.1	4.5	93.3	22	80.9	30.1	8.8
OS122B	941.7	7455.7	15.3	114.5	116.4	103.8	3.4	83.9	5.7	79.8	12.8	65.8	35.9	9.3
OS123A	840.7	316.6	31.1	180.6	171.1	125.9	8.4	46.9	7.8	136.7	25.7	94.7	69.5	12.6
OS123B	859.2	269.4	28.4	139.7	132.3	131	8.5	62.8	9.5	151.3	25.8	76.2	67.7	13.8
OS107	21.7	14.5	11.3	6.4	33.3	29.2	3.3	7.5	9.6	131.7	13.1	28	18.6	3.1
OS108	56.7	59.3	17.8	7.1	37.8	48	3	11.8	8.7	112	11.8	39.4	43	6
OS109	75	77.9	31.1	12.3	74.6	81.1	5	13.6	15.2	226.2	26.5	65.2	69.1	10
OS130	44.4	26.6	25.5	10.9	61.8	64.6	3.2	8.8	12.3	92	16.9	20.8	30	5.7
OS131	52.7	17.5	18.9	8.8	47.1	59.1	4.2	14.1	14.6	193.7	26.7	63.2	37.6	7.8

Appendix 3: German and Canadian soil guideline values

Germany -Eikmann-Kloke- Values for soil contamination
 BW III "soil value III" points to human-, phyto-, zoo-, ecotoxicological risks: remediation is required

	As mg/kg	Ba mg/kg	Cd mg/kg	Co mg/kg	Cr mg/kg	Cu mg/kg	Ni mg/kg	Pb mg/kg	Sb mg/kg	Sn mg/kg	U mg/kg	V mg/kg	Zn mg/kg	Zr mg/kg
BBodSchG	10		5	50	50	50	50	25	10	10			500	
BW III, Intervention	50	1000	20	400	350	200	200	1000	10	500	20	400	600	2000
BW III, Parks	80	2000	50	500	600	600	250	2000	20	1000	50	800	3000	3000
BW III, Industry	200	2500	60	600	800	2000	500	2000	50	1000	100	800	3000	3000

Canada - Contaminated Sites Clean up Criteria 1997 (mg/kg)

Agriculture	12		1.4			63		70						
Residential	12		10			63		140						
Commercial	12		27			100		260						
Industrial	12		27			100		400						

BBodSchG – Bundesbodenschutz- und Altlastenverordnung = German Soil Regulation 1999

Appendix 4: Analytical data of surface and seepage water

Sample ID		OW 102	OW 101	OW 100	OW 105	OW 7	OW 107	OW 106
Coordinates	Lat	-22.39582	-22.40486	-22.40952	-22.41810	-22.41827	-22.42168	-22.42250
	Long	17.15311	17.16962	17.17630	17.18065	17.18073	17.18306	17.17114
pH		8.2	3.35	4.8	3.9	6.7	7.6	3.6
Conductivity	[$\mu\text{S}/\text{cm}$]	390	364	5934	3429	800	2162	12143
Major ions	[mg/l]							
Ca		375.9	359.4	336.1	484.8	91.9	462.0	399.3
Mg		140.0	137.6	149.2	284.5	27.3	363.5	428.3
Na		94.3	89.9	101.4	171.3	34.4	127.2	179.9
K		63.77	57.87	46.52	24.38	16.36	35.83	84.95
Fe		0.1811	0.4415	3.905	64.12	0.5814	667.5	42.79
Trace elements	[mg/l]							
Al		0.353	0.524	23.070	90.650	0.412	160.000	87.090
As		0.003	0.002	0.003	0.005	0.002	0.005	0.008
B		0.074	0.077	0.075	0.031	0.134	0.029	0.094
Ba		0.036	0.048	0.027	0.011	0.088	0.006	0.020
Be		0.000	0.000	0.001	0.005	0.000	0.007	0.005
Cd		0.005	0.012	0.024	0.046	0.004	0.124	0.052
Co		0.054	0.087	0.158	0.585	0.023	1.268	0.804
Cr		0.001	0.001	0.003	0.040	0.002	0.124	0.007
Cu		0.669	1.535	5.269	24.100	0.653	7.887	7.774
Li		0.038	0.047	0.053	0.094	0.011	0.098	0.113
Ni		0.020	0.029	0.049	0.169	0.009	0.365	0.225
Pb		0.002	0.004	0.004	0.005	0.005	0.003	0.003
Ti		0.002	0.004	0.002	0.013	0.002	0.011	0.007
V		0.000	0.000	0.000	0.004	0.000	0.039	0.000
Zn		0.882	1.824	5.827	9.090	0.499	51.880	13.670

Appendix 5: Comparison of metal content in stream sediments and efflorescent salts downstream Kuruma River (Pb not detected).

		Coordinates		Zn	Cu	Ni	Co	Cr	V	Y	Sr
Efflorescence Salt		LAT	LONG	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]
OS101	Backfill plant	-22.40952	17.17630	1727.9	1782.2	30.3	94.8	29.7	11.8	25.7	27.2
OS105	Downstream	-22.39972	17.16070	984.0	1097.5	17.8	63.2	10.1	3.6	20.9	36.6
OS115	Slimes dam	-22.41810	17.18065	2290.9	4534.3	33.8	81.6	57.4	29.2	26.8	17.7
OS118	Tailings dam	-22.42250	17.17114	2045.4	593.9	34.4	88.8	2.2	1.7	34.6	21.1
Average				1762.1	2002.0	29.1	82.1	24.9	11.6	27.0	25.7
Stream sediment		LAT	LONG	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]
OS100	Backfill plant	-22.40952	17.17630	326.1	802.6	34.6	15.0	98.6	106.9	21.7	71.7
OS104	Downstream	-22.39972	17.16070	265.3	557.2	22.4	10.9	55.3	57.5	20.3	39.7
OS114	Slimes dam	-22.41810	17.18065	533.8	1734.6	35.9	22.5	96.8	107.6	28.9	70.0
OS117	Tailings dam	-22.42250	17.17114	178.6	408.3	18.5	7.3	53.1	74.3	14.4	55.1
Average				326.0	875.7	27.9	13.9	76.0	86.6	21.3	59.1
Enrichment factor salt/sediment				5.4	2.3	1.0	5.9	0.3	0.1	1.3	0.4

Appendix 6: Enrichment factors of stream sediment samples

Enrichment factor (sample/average background)						
	Zn	Cu	Cr	Ni	Co	Pb
OS117	4,3	21,3	1,1	1,0	0,9	2,7
OS127	7,5	81,8	3,1	1,8	3,2	5,6
OS126	22,7	86,0	4,8	1,9	8,9	9,6
OS124	22,1	101,3	5,0	1,9	9,7	13,7
OS114	12,7	91,3	2,0	1,9	2,8	5,9
OS125	9,8	50,9	1,7	1,7	2,2	4,3
OS128	12,1	73,2	1,7	1,2	3,1	7,0
OS100	7,8	42,2	2,1	1,8	1,9	4,0
OS102	11,2	66,3	1,5	1,3	1,7	2,0
OS129	5,9	33,7	0,8	0,9	1,4	1,9
OS104	6,3	29,3	1,2	1,2	1,4	1,4
OS107	0,5	0,8	0,7	0,6	0,8	0,8
OS106	4,1	30,6	1,3	1,1	1,0	1,8
OS113	1,0	4,8	1,0	0,8	0,8	0,8
OS112	1,4	5,9	1,1	0,9	0,8	1,4
OS132	1,2	5,3	1,2	0,8	0,8	1,1
OS108	1,4	3,1	0,8	0,9	0,9	1,3
OS109	1,8	4,1	1,6	1,6	1,5	1,5
OS110	2,6	2,4	2,0	2,5	2,1	2,4
OS111	1,9	3,6	1,3	1,3	1,3	1,3
OS135	1,1	2,0	1,3	1,0	1,1	0,7

Appendix 7: Water analyses comparison of results with the Namibian guideline values for drinking water.

ID	DESCRIPTION	Na mg/l	Mg mg/l	Ca mg/l	Ba mg/l	Be mg/l	Cd mg/l	Co mg/l	Cr mg/l	Cu mg/l	Ni mg/l	Pb mg/l	Zn mg/l
OW106	Tailings River	179.9	428.3	399.3	0.020	0.005	0.052	0.804	0.007	7.774	0.225	0.003	13.670
OW107	Kuruma River near pyrite stockpile	127.2	363.5	462.0	0.006	0.007	0.124	1.268	0.124	7.887	0.365	0.003	51.880
OW7x	Kuruma River near pyrite stockpile	34.4	27.3	91.9	0.088	0.000	0.004	0.023	0.002	0.653	0.009	0.005	0.499
OW105	Kuruma River near pyrite stockpile	171.3	284.5	484.8	0.011	0.005	0.046	0.585	0.040	24.100	0.169	0.005	9.090
OW100	Mine water at backfill plant	101.4	149.2	336.1	0.027	0.001	0.024	0.158	0.003	5.269	0.049	0.004	5.827
OW101	Kuruma River	89.9	137.6	359.4	0.048	0.000	0.012	0.087	0.001	1.535	0.029	0.004	1.824
OW103	Downstream Kuruma River	94.3	140.0	375.9	0.036	0.000	0.005	0.054	0.001	0.669	0.020	0.002	0.882
Namibia guideline values													
Group A: excellent quality		100	70	150	0.5	0.002	0.01	0.25	0.1	0.5	0.25	0.05	1
Group B: acceptable quality		400	100	200	1	0.005	0.02	0.5	0.2	1	0.5	0.1	5
Group C: low health risk		800	200	400	2	0.01	0.04	1	0.4	2	1	0.2	10
Group D: high health risk, or unsuitable for human consumption.		300	200	400	2	0.01	0.04	1	0.4	2	1	0.2	10
Standard for effluent water (maximum allowable levels)		90							0.5	1		1	5