

FROM MINE WATER TO DRINKING WATER: HEAVY-METAL REMOVAL BY CARBONATE PRECIPITATION IN THE GROOTFONTEIN- OMATAKO CANAL, NAMIBIA

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ABSTRACT

Mine water from the Kombat mine in the Otavi Mountain Land is delivered to the capital Windhoek via the 263 km long Grootfontein-Omatako canal during long drought situations when surface water is scarce. The copper-lead-zinc orebodies at Kombat and other underground mines in the Otavi Mountain Land (Tsumeb, Berg Aukas, Abenab and Abenab West) are hosted by carbonate rocks. The mine waters have in common that they have a high partial pressure of CO₂ (10^{-1.3} to 10^{-2.3} atm) and that they are oversaturated with respect to calcite. Along the course of the canal, there is a spectacular drop in CO₂ partial pressure, from 10^{-2.1} atm at the inlet of the Kombat mine to 10^{-3.5} atm at the end of the canal. This is accompanied by a drop in Ca concentration from about 60 to about 20 mg/l. The heavy metal concentrations (Cd, Cu, Mn, Pb and Zn) drop along the course of the canal to values far below the national drinking water standard. Scavenging by calcium carbonate precipitation is the major depletion mechanism for Cd, Mn, Pb and Zn, whereas Cu probably is also removed by precipitating oxidic Cu minerals. Adsorption on hydrous ferric oxide is very subordinate. The potential ground water yield of the Kombat mine is 5 million m³/year. A total yield of 20 million m³/y is expected when the remaining mines in the Otavi Mountain Land are connected to the canal. Drinking water quality at the end of the canal can be predicted for all heavy metals except for Cd of the waters from the Tsumeb mine. Nevertheless, the canal should not be used as exclusive dump site for heavy metals. It is feasible to precipitate sufficient carbonate in a cleaning pond before delivering the water to the canal.

INTRODUCTION

The Grootfontein-Omatako canal is part of the Eastern National Water Carrier, linking the Otavi Mountain Land in northern Namibia and the capital Windhoek (Figure 1). In 1997, the canal offered a good opportunity to study large-scale heavy metal scavenging by precipitating carbonate. Water from only a single source, the lead-zinc-copper underground mine at Kom-

bat, was delivered to the canal in 1997, when the chemical changes along its course were investigated.

The Kombat mine can yield 5 million m³ per year. Water from other underground mines in the Otavi Mountain Land also constitute a large potential source of drinking water. The Tsumeb mine, active at the time of sampling but closed since 1998, and the dormant Berg Aukas, Abenab and Abenab West mines have a total yield of about 15 m³ per year (Figure 2). The waters

from the dormant mines are earmarked to be supplied to the canal. These waters were also sampled in order to make predictions on their chemical behaviour.

This research was conducted under a technical co-operation program between Namibia and Germany. The partners in the groundwater exploration project were the Department of Water Affairs (DWA, Windhoek), Namibian Water Corporation and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover).

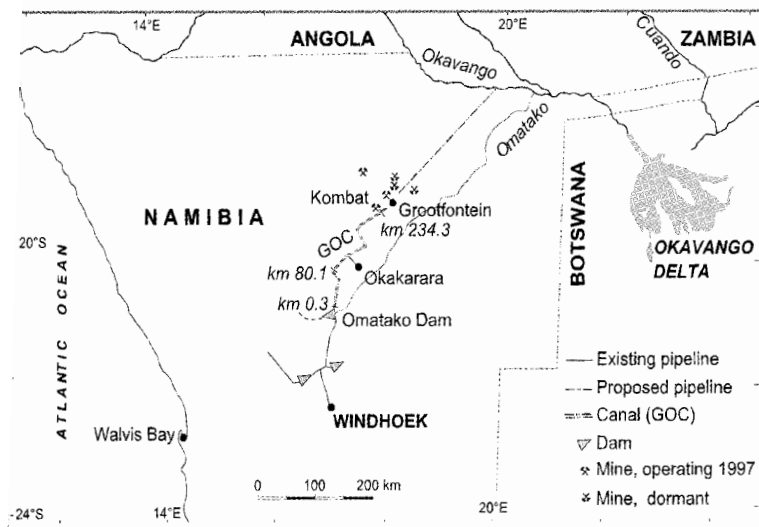


Figure 1. Location of the Grootfontein-Omatako canal (GOC), Namibia.

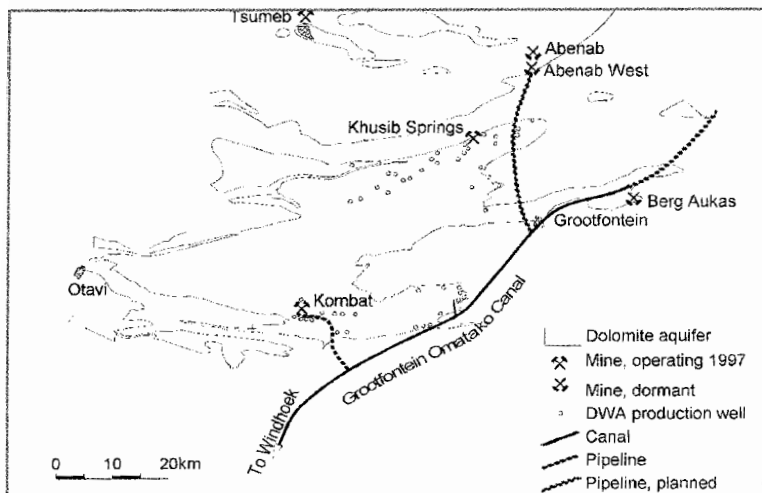


Figure 2. Location of mines in the Otavi Mountain Land, Namibia.

MINES IN THE OTAVI MOUNTAIN LAND

The Otavi Mountain Land in northern Namibia is a dolomitic massif rising up to 500 m above the surrounding plain. Its four synclines composed of fractured dolomite comprise one of the most important groundwater sources of Namibia despite the fact that their recharge depends on rare excessive rainfall events. The mean annual rainfall of 550 mm is high compared to the country-wide average of 250 mm. It is difficult to intercept

the groundwater flux by wells due to its heterogeneous character. However, the cavities produced by underground mining represent easily accessible groundwater. The Pb-Zn(-Cu) ore-bodies were emplaced along hydraulically favourable structures such as paleokarst and fault conduits (Geological Survey, 1992). The depth of mining is 800 m at Kombat, 1800 m at Tsumeb, 800 m at Berg Aukas, 215 m at Abenab and 380 m at Abenab West.

The degree of supergene oxidation of the sulphide ore prior to mining varies considerably and may reach unusual depths of 1500 m, as shown by the Tsumeb deposit. Despite the relatively high proportion of oxidized ore, mobilisation of heavy metals and, hence, pollution of mine waters, is strongly inhibited by the ubiquitous presence of carbonate.

THE GROOTFONTEIN-OMATAKO CANAL

The Grootfontein-Omatako canal was built between 1981 and 1987. The Kombat mine is connected to the canal via a 20 km long pipeline. The length of the canal is 263 km, of which 203 km are open and concrete-lined and the remainder consists of 23 inverted siphons or underground pipeline. The canal has a maximum width of 3.7 m and a maximum depth of 1.65 m. It is a gravity flow canal with a gentle slope of about 1:3000. When full, the flow velocity is 0.8 m/s. At the time of sampling in March 1997, the estimated flow velocity was 0.4 m/s at km 80.21.

Water from the Kombat mine has been delivered to the Omatako dam during test runs in 1997. It is intended to supply water from Kombat and other underground mines in the Otavi Mountain Land to the capital Windhoek during long droughts, when surface water becomes scarce. Up to now, Kombat mine water has been treated at Okakarara in order to meet rural water demand in that area.

There have been plans to link the canal via a 240 km long pipeline to the Okavango River. Disastrous consequences for the fauna and flora in this unique game reserve would result if the Okavango water were diverted to Windhoek. All alternatives, including those described in this paper, deserve to be seriously evaluated.

SAMPLING AND ANALYTICAL METHODS

The water samples of the Kombat mine were taken from the raw water reservoir of the main shaft (sample 1008) and from the pipeline inlet into the Grootfontein-Omatako canal (sample 1007 at km 234.29). The pumping rate was 1,400 m³/h in March 1997. The water sample of the Tsumeb mine was collected from Shaft No. 1 in July 1997, when the pumping rate was 220 m³/h.

The water sample from the Berg Aukas mine was taken with a 5-litre PVC bailer at 743 m below water level. The same bailer was used for sampling the Abenab West and Abenab mines at 80 - 100 m below water level.

The water samples taken in March 1997 from the Kombat and Berg Aukas mines and from the Grootfontein-Omatako canal, which were analysed for minor elements in the BGR laboratory, were acidified with 1 vol. % HNO_3 (65 %) to $\text{pH} < 2$; these samples were not filtered. In contrast, the water samples for minor element analysis taken at the Tsumeb, Abenab West and Abenab mines in July 1997 were filtered through a $0.45 \mu\text{m}$ membrane prior to acidification. The minor elements were determined by inductively coupled plasma mass spectrometry (ICP-MS). The water samples for analysis of major elements were not filtered or acidified.

The analyses of unfiltered samples tend to overestimate the concentration of heavy metals, because mine waters contain suspended particles, which may dissolve during acidification prior to laboratory analysis. In contrast, the analyses of filtered samples tend to underestimate the concentrations of heavy metals because scavenging by precipitating phases (such as carbonates) during filtration takes place.

CHEMICAL COMPOSITION OF MINE WATER

The water samples from the underground mines have high partial pressure of CO_2 ($10^{-1.3}$ to $10^{-2.3}$ atm), i.e. considerably higher than that of atmospheric CO_2 ($10^{-3.5}$). The waters are also supersaturated with respect to calcite and dolomite. The water from the different mines varies considerably with respect to heavy metal concentration (Cd, Cu, Mn, Pb and Zn), partly reflecting the composition of the respective ore. This paper focuses on geochemical modelling; it is based on samples taken in March and July 1997 and analysed in the BGR laboratories. Water samples taken between 1980 and 1995 and analysed in other laboratories are reviewed by Ploethner et al. (1998). They are not included in the modelling for the sake of analytical consistency. However, the predictions would not be significantly different if they were based on analyses from other laboratories.

CHEMICAL COMPOSITION OF WATER FROM THE GROOTFONTEIN-OMATAKO CANAL

Along the length of the canal, there is a spectacular drop in CO_2 partial pressure, from approximately $10^{-2.1}$ at the inlet from the Kombat mine to $10^{-3.5}$ atm at the end of the canal (Figure 3, Table 1). This is accompanied by a drop in Ca concentration, which decreases from about 60 to about 20 mg/l. The CO_2 degassing produces calcium carbonate precipitation.

The Mg concentrations remain nearly unchanged (approximately 50 mg/l), and the degree of supersaturation with respect to dolomite increases along the course of the canal. Precipitation of dolomite is inhibited for kinetic reasons.

Heavy metal concentrations drop along the length of the canal. Scavenging by precipitating carbonate is the major depletion mechanism for heavy metals. Note that the authors do not approve that the canal be used as exclusive dump site for heavy metals. It is feasible to precipitate sufficient carbonate in a settling pond prior to delivering the water to the canal. This paper elucidates the heavy metal removal by carbonate precipitation. The results are intended to be used in the layout of settling ponds.

DISTRIBUTION COEFFICIENTS

The mineralogical composition of the precipitate in the canal is not known. Thermodynamically stable calcite or metastable aragonite are possible carbonate phases. There are thermodynamic and kinetic data which can be used to estimate the partitioning of heavy metals between a liquid and a solid Ca carbonate phase. Nearly all relevant experimental and theoretical investigations are based on calcite and not on aragonite. Therefore, the model presented in this paper is based on calcite.

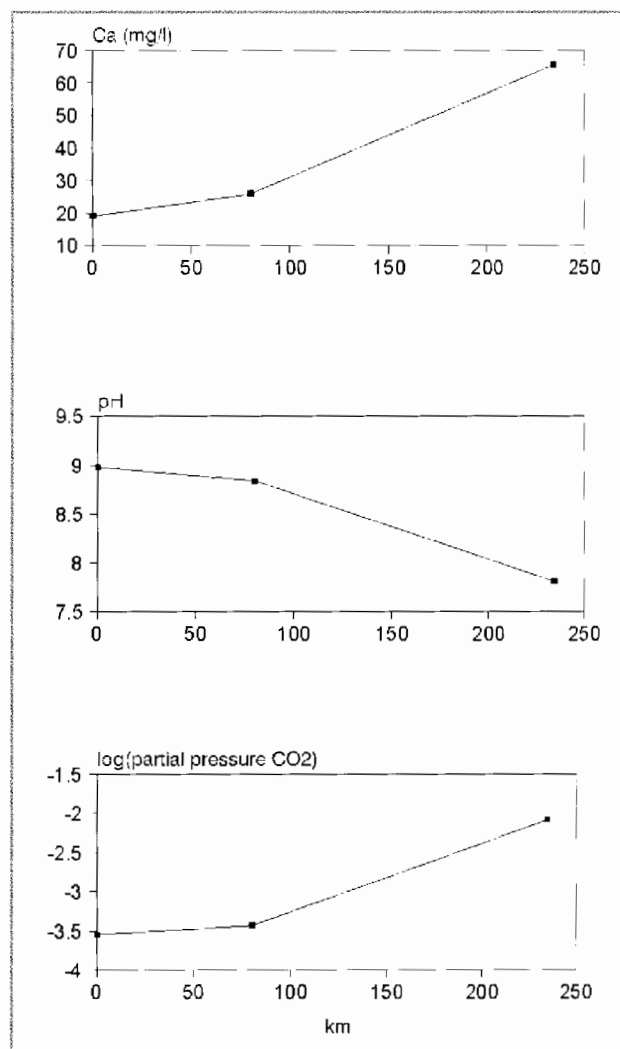


Figure 3. Ca concentration, pH and log partial CO_2 pressure (atm) of the water in the Grootfontein-Omatako canal. Only water pumped from the Kombat mine entered the canal (at km 234.29).

The distribution coefficient D for the partitioning of a divalent heavy metal between calcite and an aqueous phase, is reported in two different forms:

$$D_{Me^{+2}} = \frac{[Me^{+2}/Ca^{+2}]_{\text{calcite}}}{[Me^{+2}/Ca^{+2}]_{\text{liquid}}} \quad (1)$$

where $[Me^{+2}/Ca^{+2}]$ is the ratio between the free heavy-metal cation concentration (Cd^{+2} , Cu^{+2} , Mn^{+2} , Pb^{+2} or Zn^{+2}) and Ca^{+2} cation concentration;

$$D_{Me(\text{apparent})} = \frac{[Me/Ca]_{\text{calcite}}}{[Me/Ca]_{\text{liquid}}} \quad (2)$$

where $[Me/Ca]_{\text{liquid}}$ is the ratio between the total divalent heavy-metal concentration [$Cd(II)$, $Cu(II)$, $Mn(II)$, $Pb(II)$ or $Zn(II)$] and total $Ca(II)$ concentration in the liquid, and $[Me/Ca]_{\text{calcite}}$ is the ratio between the heavy metal and Ca concentration in calcite coexisting with the liquid. For modelling purposes, the apparent distribution coefficient ($D_{Me(\text{apparent})}$) is the most convenient para-

meter because it allows predictions to be made in a mathematically simple form.

Distribution coefficients depend strongly on precipitation rates. Generally speaking, distribution coefficients >1 decrease and distribution coefficients <1 increase, as precipitation rates increase; in both cases, the distribution coefficient approaches 1 (Lorens, 1981; Tesoriero and Pankow, 1996). Table 2 lists the experimental $D_{Me(\text{apparent})}$ values for Cd and Mn for low precipitation rates (about 0.03 nmol/min.mg) and high precipitation rates (about 300 nmol/min.mg). The precipitation rate increases with the saturation index of calcite, defined as the logarithm of the ratio between the product of the Ca^{+2} and CO_3^{2-} concentrations in the solution to the solubility product of calcite. The exact relationships have not been established experimentally, but the data

	Grootfontein-Omatako canal (km ~0.3), downstream of Omatako Dam by-pass	Grootfontein-Omatako canal (km 80.21)	Grootfontein-Omatako Canal (km 234.29), inlet of Kombat Mine Pipeline	Kombat mine (Main shaft)	Berg Aukas mine (Shaft 2)	Tsumeb mine (Shaft 1)	Abenab West mine	Abenab mine
Sample No.	1004	1005	1007	1008	1010	1020	1022	1024
Sampling date	01.03.97	02.03.97	03.03.97	03.03.97	04.03.97	22.07.97	22.07.97	22.07.97
Field measurements								
Temperature	28.7	28.6	25.5	26.3	27	28.2	24.7	20.9
pH	8.98	8.84	7.81	7.95	7.15	6.99	7.06	7.06
pe	5.34	5.51	7.26	7.07	6.21	3.86	6.40	1.886
$\log(pCO_2)^{**}$	-3.55	-3.43	-2.08	-2.26	-1.35	-1.55	-1.25	-1.3
HCO_3^- (total C)	299.4	280.3	590.7	526.6	746.3	366.2	813.3	772.1
Filtration	no	no	no	no	no	yes	yes	yes
Major element concentrations (mg/l) [laboratory analyses]								
K	3.5	4.77	3.5	4.96	1.35	21.1	0.7	1.7
Na	5.51	4.77	4.17	3.81	4.94	160	5.8	9.7
Cl	8.34	9.1	6.41	6.49	5.1	78.6	2.9	5.1
Mg	53.6	49.5	47.5	44.8	56.8	155	94.5	97.3
Ca	19	25.9	61.1	55.6	100.7	454	71.8	54.6
SO_4^{2-} (total S)	49.4	62.2	50.1	40.9	21.5	1807	7.11	0.55
SiO_2 (total Si)	17.9	17.7	17.7	18.2	20.7	20.5	28.8	24
Minor element concentrations (mg/l) [laboratory analyses]								
Al	0.12	0.083	1.62	1.59	0.0089	<0.001	0.0011	0.0017
Cd	0.00013	0.000090	0.0016	0.0011	0.0015	0.15	0.00016	0.00014
Cu	0.0037	0.0018	0.59	0.45	0.0020	0.0045	0.0012	0.0046
Fe	0.10	0.081	1.9	1.72	0.042	0.12	0.073	3.6
Mn	0.010	0.012	1.00	0.59	0.0032	2.3	0.016	0.44
P	0.021	0.012	0.16	0.45	0.0076	0.0096	0.020	0.020
Pb	0.0011	0.00063	1.21	0.27	0.019	0.10	0.0050	0.0020
Zn	0.026	0.0041	0.15	0.109	0.70	6.55	0.047	0.060

* At the time of sampling, only water from the Kombat mine entered the canal

** \log partial CO_2 pressure (atm) derived from the total concentration of aqueous C species

Table 1. Chemical analyses of water from the Grootfontein-Omatako canal, the Kombat* and Berg Aukas mines (sampling period 1 – 4 March 1997) and the Abenab West and Abenab mines (sampling 22 July 1977).

of Lorens (1981) suggests that high precipitation rates (about 300 nmol/min.mg) are compatible with a calcite saturation index of about 1, i.e. the saturation index for calcite along the whole length of the Grootfontein-Omatako canal.

For Cu and Zn, the exact relationships between the distribution coefficient and precipitation rate are not known. The experiments of Kitano et al. (1980) yield a high distribution coefficient for Zn ($D_{Zn(apparent)}=25$), whereas Crocket and Winchester (1966) determined a low partition coefficient ($D_{Zn(apparent)}=4$). Different set-ups were used for the experiments. It can be assumed that $D_{Zn(apparent)}=25$, which is close to the ratio of the respective solubility products (K_{CaCO_3}/K_{ZnCO_3}), corresponds to a low precipitation rate and $D_{Zn(apparent)}=4$ to a high precipitation rate. In an analogous manner, it is assumed that $D_{Cu(apparent)}=25$ (Kitano et al., 1980), which is close to the ratio of the respective solubility products (K_{CaCO_3}/K_{CuCO_3}), corresponds to a low precipitation rate. The extrapolation of this distribution coefficient to a high precipitation rate corresponds approximately to $D_{Cu(apparent)}=4$, if a relationship analogous to those of Cd, Mn or Zn is assumed.

Since no experimental data are available for Pb partitioning, $D_{Pb}+2$ has to be estimated by interpolation of data for other metals. The activity coefficient of the solid phase trace component (γ_{MeCO_3}) can be calculated, assuming that the activity of the $CaCO_3$ component (γ_{CaCO_3}) is unity and the Me^{+2}/Ca^{+2} concentration ratios equal Me^{+2}/Ca^{+2} activity ratios:

$$\gamma_{MeCO_3} = (K_{CaCO_3}/K_{MeCO_3}) / D_{Me}+2 \quad (3)$$

where K_{CaCO_3} and K_{MeCO_3} are the solubility product constants of $CaCO_3$ and $MeCO_3$ (e.g. $PbCO_3$). Experimental true distribution coefficients ($D_{Me}+2$) are available for Ba, Cd, Fe, Mg and Sr. Experimental apparent distribution coefficients ($D_{Me(apparent)}$) are available for another five metals (Co, Cu, Mn, Ra and Zn). The activity coefficient (γ_{MeCO_3}) increases with the absolute value of the difference in ionic radius $|r_{Ca} - r_{Me}|$ between Ca^{+2} and Me^{+2} . Small cations (Cd^{+2} , Co^{+2} , Cu^{+2} , Fe^{+2} , Mg^{+2} , Mn^{+2} and Zn^{+2}) correspond to a smaller increase of the activity coefficient than large cations (Ba^{+2} , Ra^{+2} and Sr^{+2}) because the calcite lattice accommodates small cations more readily than large cations.

Plotting γ_{MeCO_3} versus $|r_{Ca} - r_{Me}|$, the value for γ_{PbCO_3} can be interpolated by cubic regression (Figure 4). Using the curve:

$$y = a + bx + cx^2 + dx^3$$

for γ_{MeCO_3} derived from $D_{Me}+2$ (dotted line), $\gamma_{PbCO_3} = 10^{2.25}$ is obtained. The same value for γ_{PbCO_3} corresponds to the regression of all γ_{MeCO_3} (solid line), which are derived from both $D_{Me}+2$ and $D_{Me(apparent)}$.

The distribution coefficient $D_{Pb}+2$ is calculated from $\gamma_{PbCO_3} = 10^{2.25}$, using the solubility product constant for $PbCO_3$, which is in the range of $10^{-13.5}$ to $10^{-12.8}$ according to various authors, and the solubility product constant for $CaCO_3$ ($10^{-8.29}$):

$$D_{Pb}+2 = 10^{-8.29 + 13.5 - 2.25} = 910$$

or

$$D_{Pb}+2 = 10^{-8.29 + 12.8 - 2.25} = 180$$

These very high values correspond to low precipitation rates or equilibrium. Note that a very high distribution coefficient

has also been determined for Cd near equilibrium conditions ($D_{Cd}+2=1240$; (Tesoriere and Pankow, 1996), whereas $D_{Cd(apparent)}$ is as low as 10 at high precipitation rates (Lorens, 1981). In analogy to Cd, $D_{Pb(apparent)}=10$ is considered to be a suitable value for the modelling carried out below (see underlined distribution coefficients in Table 2).

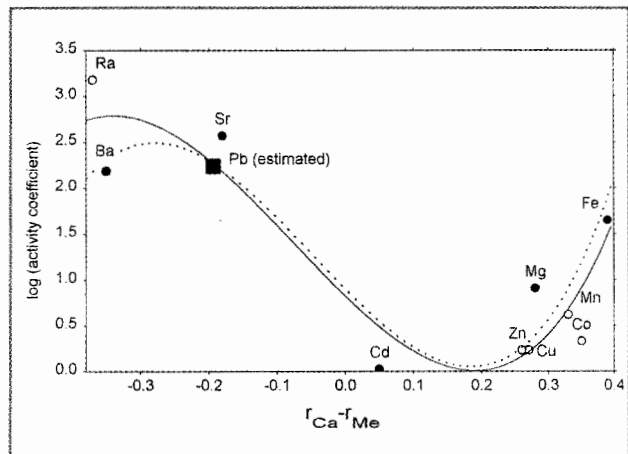


Figure 4. Log of the activity coefficient ($\log \gamma_{MeCO_3}$) of the solid phase trace component ($MeCO_3$) in calcite versus difference in ionic radii between Ca^{+2} and Me^{+2} ($r_{Ca} - r_{Me}$). The solid circles refer to activity coefficients derived from $D_{Me}+2$ and the open circles refer to activity coefficients derived from $D_{Me(apparent)}$. The dotted line is the cubic regression ($y = a + bx + cx^2 + dx^3$) of data derived from $D_{Me}+2$ and the solid line is the cubic regression of all data. See text for explanation.

	Low precipitation rate (or equilibrium)			High precipitation rate (nonequilibrium)		
	$D_{Me}+2$	$D_{Me(apparent)}$	References	$D_{Me}+2$	$D_{Me(apparent)}$	References
Cd	1240	70	Lorens (1981), Tesoriere and Pankow (1996)	200	<u>10*</u>	Lorens (1981), Tesoriere and Pankow (1996)
Cu		25	Kitano et al. (1980)		<u>4</u>	See text
Mn		51	Lorens (1981)		<u>6</u>	Lorens (1981)
Pb	180-910		See text		<u>10</u>	See text
Zn		25	Kitano et al. (1980)		<u>4</u>	Crocket and Winchester (1966)

* The underlined apparent distribution coefficients are used for predicting the composition of the water in the Grootfontein-Omatako canal.

Table 2. Distribution coefficients $D_{Me}+2$ and $D_{Me(apparent)}$ for the partitioning of divalent trace metals between liquid and calcite at 25°C.

PREDICTING CHEMICAL CHANGES IN WATER FROM THE KOMBAT MINE

The chemical composition of the water changes along the length of the canal and, accordingly, the heavy metal-calcium ratio of the precipitating calcite. This case is described by the heterogeneous distribution law of Doerner and Hoskins (1925; quoted by McIntire, 1963):

$$\ln[Me_{initial}/Me_{final}] = D \ln[Ca_{initial}/Ca_{final}] \quad (4)$$

where $[Ca_{initial}/Ca_{final}]$ is the ratio between Ca concentration in the water before crystallization of calcite (mine water reservoir) and Ca concentration at the end of crystallization

of calcite (at a given position along the canal) and $[Me_{initial}/Me_{final}]$ is the corresponding heavy metal concentration ratio.

The Kombat mine water has a Ca concentration of 55.6 mg/l. After flowing 154 km through the canal (from km 234.29 to km 80.21), the Ca concentration decreases to 25.9 mg/l. The concentration ratio $55.6/25.9=2.15$, has been used to predict the heavy metal concentrations in the canal at km 80.21 (Figure 5).

The modelling produces satisfactory results for Mn and Zn (Figure 5, prediction A). The depletion of Pb is slightly overestimated, whereas the depletion of Cd is considerably overestimated by the model. Predicted and actual concentration are in agreement for $D_{Pb(apparent)}=8$ (instead of 10) and $D_{Cd(apparent)}=3.3$ (instead of 10). The mine water is supersaturated with respect to the phosphates hydroxyapatite, pyromorphite and strengite. It is possible that precipitating pyromorphite also removes some Pb.

The predicted Cu concentration is higher than the actual value. Variations in Cu concentrations cannot be attributed to calcite precipitation alone. The mine water is supersaturated with respect to azurite, cuprous ferrite, malachite and tenorite. Precipitation of these phases may remove Cu dissolved in the water.

The effect of adsorption on hydrous ferric oxide is only minor. If the adsorption on hydrous ferric oxide is taken into consideration in addition to calcite scavenging, the predicted heavy metal concentrations (prediction B) are little different from those based on calcite precipitation alone (prediction A). Prediction B produces slightly lower values for Cu than prediction A, whereas the values for the other heavy metals are nearly identical (Figure 5).

PREDICTING CHEMICAL CHANGES IN WATER FROM OTHER MINES

The Tsumeb, Berg Aukas, Abenab West and Abenab mines have not supplied water to the Grootfontein-Omatako canal yet. The expected chemical changes undergone by the water from these mines, as it flows through the canal, has been modelled using two different procedures (Figure 6):

- Prediction A (theoretical model) is based on calcite precipitation alone, using the apparent distribution coefficients in Table 2 (underlined values) and the calcium depletion ratio $[Ca_{initial}/Ca_{final}]=2.15$ (same procedure as used for the case of the Kombat mine, see above).
- Prediction C (empirical model) uses the heavy metal depletion ratio observed for water from the Kombat mine, e.g.

$$[Me_{initial}/Me_{final}]_{Tsumeb} = [Me_{initial}/Me_{final}]_{Kombat} \quad (5)$$

The theoretical model (prediction A) is likely to produce satisfactory results for Mn, Pb and Zn. In the case of Cu, the theoretical model (prediction A) should be regarded as a minimum value for Cu removal. A more realistic value is produced by the empirical model (prediction C).

The interpretation of the results for Cd is problematic: the empirical model predicts that $D_{Cd(apparent)}$ is as low as 3.3; this value is not supported by experimental data. The Cd concentrations are only critical in the case of the Tsumeb mine. However, even the empirical model forecasts a Cd concentration close to the national drinking water standard (0.01 mg/l Cd) after the water from the mine has passed through the Grootfontein-Omatako canal. For Cu, Mn, Pb and Zn, drinking water quality is predicted by both models (<0.5 mg/l Cu, <0.05 mg/l Mn, <0.05 mg/l Pb and <1 mg/l Zn).

CONCLUSIONS

A note of caution is justified when laboratory-derived or theoretical distribution coefficients (synthetic systems) are applied to large-scale carbonate precipitation in the field (natural systems). The overestimation of Cd scavenging by calcite is indeed a matter of concern, because Cd is nearly exclusively captured by carbonate in the absence of sulphides. There is a danger of overestimating the effect of heavy-metal scavenging by calcite. This deserves to be noted despite the fact that predicted and actual values for Mn, Pb and Zn agree quite well and Cu scavenging is even underestimated. If the distribution coefficient used for Cd leads to overestimating scavenging by precipitating carbonate, then it may be suspected that the distribution coefficients used for Cu, Mn, Pb and Zn may also be too high.

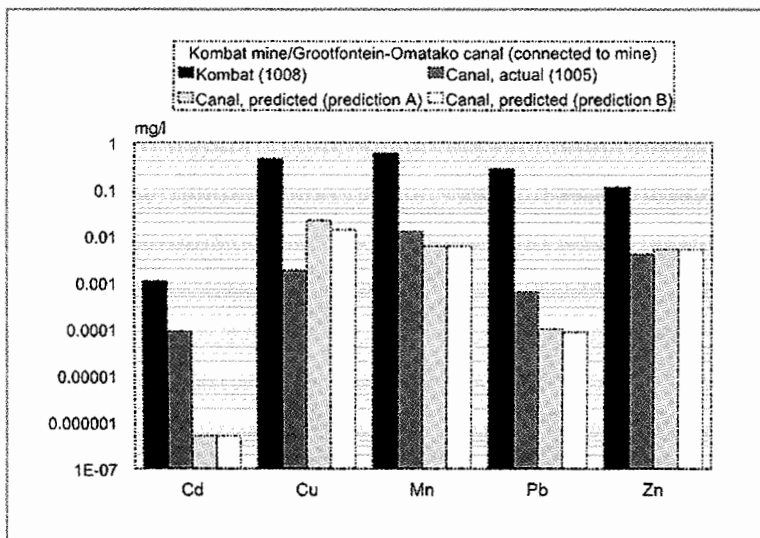


Figure 5. Histogram showing the heavy metal concentration of water in the Kombat mine as well as the predicted and actual composition of the water in the Grootfontein-Omatako canal at km 80.21. Prediction A takes only heavy metal removal by calcite precipitation into consideration. Prediction B takes both adsorption on hydrous ferric oxide and calcite precipitation into consideration.

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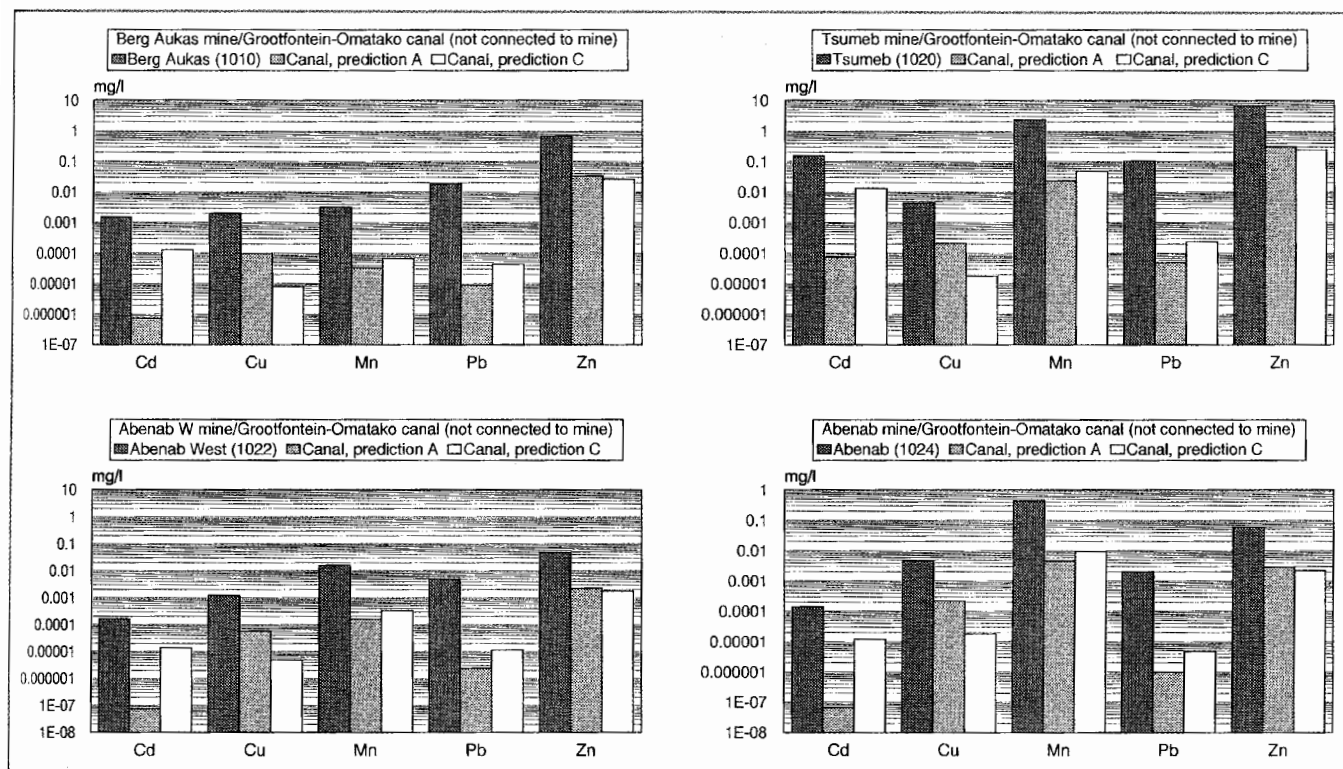


Figure 6. Histograms showing the heavy metal concentrations of water from the Berg Aukas, Tsumeb, Abenab West and Abenab mines as well as the predicted composition of water in the Grootfontein-Omatako canal at km 80.21 for the theoretical case that only water from the individual mine enters the canal. Prediction A is based on a theoretical model (only calcite precipitation) and prediction C is based on an empirical model. See text for explanation.

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