CHAPTER 5 GOLD MINE TAILINGS AS A SOURCE OF CONTAMINATION

5.1 INTRODUCTION

The purpose of this chapter is to show that the gold mine tailings at Machavie gold mine is a source of trace element contamination. Trace element concentrations in the sulphates of the ore were determined, as well as the concentrations of certain water soluble trace elements in salts that precipitated on the surface of the reworked tailings, down-slope of tailings dam number 4. The pH and electrical conductivity (EC) of tailings covering the investigated soils were determined. Soils underlying the derived tailings were also tested for pH and EC to establish if acidic leachate, originating from the tailings, has affected the underlying soils.

The extent of contamination in the investigated areas is characterized by comparing total trace element concentrations in the tailings and soils with the Dutch soil standards after Moen, Cornet & Evers (1986).

5.2 METHODOLOGY

For geochemical analyses, all soil samples were dried at 40°C and disaggregated by using a mortar and pestle. Visible organic matter was removed. The samples were sieved to obtain the finer than 2 mm soil fraction which was milled to be finer than 75 micron. Powder briquettes were pressed from the < 75 micron fraction, using a PVA binder. The samples were analysed for their trace element content with a Philips PW 1606 Simultaneous X-ray Fluorescence Spectrometer (SXRF) (Appendix C). The finer than 2 mm soil fraction is recommended for environmental studies by various authors (e.g. Schloemann (1994) and Alloway (1995)).

The paste pH (water) of all the samples was determined according to the TMH method

(THM1,1990). Electrical conductivity (EC) of the soil and tailings samples was determined according to the soil paste method (TMH1, 1990). The EC of a soil is an indirect measure of the total dissolved solids (TDS) present in a soil. TDS has a negative impact on plant growth due to increased osmotic pressure of the soil solution which inhibit water and nutrient uptake by plants. According to Deuel & Holliday (1994) most crops will be affected at an EC of greater than 400 mS/m, and this value is usually prescribed as a soil cleanup guideline.

5.2.1 Analyzed elements

The Philips PW 1606 Simultaneous X-ray Fluorescence Spectrometer analyses were done for the following elements: TiO_2%, MnO%, Fe_2O_3 t %, Sc, V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Ba, W, Pb, Th, U. For this study, the elements As, Co, Cr, Cu, Ni, Pb and Zn were selected as they have adverse effects on human and livestock health, aquatic ecosystems as well as crop yield and soil sustainability, when present in elevated concentrations (Department of Water Affairs and Forestry[1,2,3,4],1996). In addition, all these elements (except Co) appear on the priority pollutants list of the United States Environmental Protection Agency (Deutsch, 1997).

Table 5.1 Detection limits for the Philips PW 1606 Simultaneous X-ray Fluorescence Spectrometer (after Elsenbroek, 1996). All values in mg/kg.

	As	**Co**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Udl	412	210	2900	1230	2380	636	680
Lld	10	10	4	9	10	4	3

Udl = Upper detection limit and Lld = lower limit of detection.

5.3 TAILINGS AS A SOURCE OF TRACE ELEMENT CONTAMINATION

Trace elements that are geochemically associated with sulphide minerals (e.g. pyrite) are termed chalcophile and include (amongst others) Cd, Cu, Ag, Au, Zn, Hg, Pb, As, Sb, Se, Tl and Mo

(Alloway, 1995). Barton & Hallbauer (1996), ascribe the gold/sulphide mineralisation present in the Black Reef Formation to sedimentological deposition of gold bearing sulphate minerals at ~ 2500 Ma. Table 5.2 contains some maximum average trace element concentrations of pyrite of the Black Reef formation.

Table 5.2. The average maximum trace element content (AMTEC) of pyrite of the Black Reef Formation in mg/kg (after Barton & Hallbauer, 1996).

Element	**Cu**	**Co**	**Ni**	**Ba**	**Cd**	**Cr**	**Mn**	**Ag**	**Au**	**Bi**	**Sr**
AMTEC (ppm)	346	1006	1930	12	0,5	33	16	21	1,5	201	3
Element	**Ti**	**Pb**	**As**	**Zn**	**Na**	**Ca**	**Al**	**Mo**	**Te**	**Se**	**Sb**
AMTEC (ppm)	98	844	1394	90	224	1020	1317	14	21	<0,02	137

Ore samples from the Machavie waste rock dump were collected and crushed. The resulting material was sieved and the fraction finer than 0,150 mm and coarser than 0,075 mm was used to extract the sulphide minerals by means of a gravimetric procedure. Tetrabromoethane with a specific gravity of 2,96 was used to separate the sulphide minerals in the sample from the host rock minerals. The resulting material was analysed on a Philips X-ray diffraction unit which uses Ziemans diffrac 80 software. The sample is composed of 99 per cent pyrite and 1 per cent quartz. The trace element composition of these collected pyrite samples, as measured by the Philips PW 1606 Simultaneous X-ray Fluorescence Spectrometers, is presented in Table 5.3.

Table 5.3 Trace element composition (in mg/kg except Fe_2O_3 t and MnO) of pyrite of the Black Reef Formation from the discard ore dump at Machavie gold mine.

Fe*	**Mn****	**As**	**Ba**	**Co**	**Cr**	**Cu**	**Mo**	**Ni**	**Pb**	**Sn**	**Th**	**U**	**V**	**Zn**
0 %	0,12 %	585	1151	2873	9502	420	0	561	0	0	0	0	99	266

**Fe as Fe_2O_3 (t) and **Mn as MnO*

It is evident from Tables 5.2 and 5.3 that the pyrite in the Black Reef Formation contains high concentrations of some trace elements, particularly As, Ba, Co, Cr, Cu, Ni and Zn. Since gold is associated with the pyrite in the ore of the Black Reef Formation (Barton & Hallbauer, 1996), pyrite rich material would have been mined at Machavie Gold mine. After processing the pyrite rich slimes, the resulting waste stream was then discarded as tailings dams. Tables 5.2 and 5.3 show that high concentrations of certain trace elements can be expected in the tailings dams. The tailings can therefore be regarded as a potential source of trace element contamination.

5.3.1 Salts precipitated on the tailings dams.

According to Lloyd (1997), salts precipitate on the surface of tailings dams as a result of upward capillary movement of salt-rich liquids. In times of water deficit (e.g. winter months in the North-West Province of South Africa) the salt-rich solutions evaporate and cause the deposition of salts. These salt deposits are usually soluble and rich in trace elements (Spotts, Schafer, Luckay, & Mitchell, 1997). Predominantly whitish and some yellowish salt precipitations were observed on the surface of reworked tailings as well as on the sides of the tailings dams. Plate 5.1 shows the extent of salt precipitation on the paddocked tailings adjacent to tailings dam number 4. Plate 5.2 shows a close-up of the precipitations.

Plate5.1

The extent of soluble salts deposited on the paddocked tailings adjacent to tailings dam number 4.

Plate5.2

Close-up of the yellowish and white soluble salts deposited on the paddocked tailings adjacent to tailings dam number 4.

Samples of both the yellowish and whitish precipitates were taken from paddocked tailings adjacent to tailings dam number 4. Mineralogical analyses showed that the whitish precipitate is composed of Halotrichite $Al_2Fe(SO_4)_4{\cdot}22H_2O$; Hexahydrite $MgSO_4{\cdot}6H_2O$; Alunogen $Al_2(SO_4)_3{\cdot}17H_2O$; Melanterite $FeSO_4{\cdot}7H_2O$ and Thenardite Na_2SO_4. The yellowish precipitate is mostly composed of Fe-sulphates, including compounds such as Coquimbite $Fe_2(SO_4)_3{\cdot}9H_2O$; Metavoltine $Na_6K_2Fe_7(SO_4)_{12}O_2{\cdot}18H_2O$ and Copiapite $Fe_{14}O_3(SO_4)_{18}{\cdot}63H_2O$.

The water soluble trace element content of the salts was determined by adding equal weights of each precipitate to de-ionised pure water (having a conductivity of 18 MΩ). Equal weights of precipitate and water were shaken for two hours and filtered through a Watmann number 40 filter paper. The resulting liquid was analysed for As, Cd, Co, Cr, Cu, Ni, Pb and Zn using the ICP-AES technique and the results are shown in Table 5.4.

Table 5.4 Water soluble concentrations of As, Cd, Co, Cr, Cu, Ni, Pb and Zn (mg/l) in the white and yellow precipitate occurring on the paddocked tailings.

Precipitate	**As**	**Co**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
White	*bdl*	109,09	14,97	63,74	939,75	4,35	369,58
Yellow	303,26	30,37	15,01	40,78	93,79	34,13	113,81

bdl: Concentration below the detection limit of the ICP-AES instrument.

It is evident from the soluble trace element concentrations present in the sulphate precipitates that these sulphate salts, originating from the tailings dams, are a potential source of trace element contamination. In addition, these results also prove that leachate, rich in trace elements, is produced within the tailings.

5.4 THE INFLUENCE OF THE TAILINGS ON THE pH AND EC OF THE UNDERLYING SOILS

The gold mine tailings produces acidic leachate as discussed in Chapter 2, due to the oxidation of pyrite and other sulphide minerals. The acidity and associated trace elements will leach into the underlying soils under normal soil drainage conditions. There are a number of natural buffering reactions that occur in soils that can partially or completely neutralize the acidity. Cations and anions are released by these neutralization reactions and increase the total dissolved solids content (TDS) and the electrical conductivity of the soil solution (James, 1997). The production of sulphate during sulphide mineral oxidation will further increase the salt content of the soil. By examining the pH and conductivity of the soils of the study area, it can be established if the soils are affected by the overlying reworked tailings.

5.4.1 Tailings

Statistical analyses of all the tailings samples (n = 30) show the material to be strongly acidic with an average pH of 3,43. A minimum pH of 2,50 was measured in sample MT 25/1 and a maximum of 4,63 was measured in sample MT 16/1. These results confirm that the tailings produce acidic leachate. The acidity and associated trace elements will leach into the underlying soils under normal soil drainage conditions and adversely affect the pH of the underlying soils. The corrosiveness of the acidic leachate is shown in Plate 5.3 showing metal drums embedded in the tailings that are disintegrating.

Conductivity analyses of the tailings showed the material to have a conductivity ranging between 1,15 mS/m to 171,10 mS/m. These values are well below the threshold level of 400 mS/m.

Plate 5.3

Metal drums in tailings dam number 4, corroded due to the acid nature of the tailings.

5.4.2 Colluvial soils

Colluvial soil unit CU is very strongly acidic with a pH range of 3,26 - 4,70. The underlying nodular ferruginised unit CF is strongly to slightly acidic with pH values ranging from 3,13 - 6,30. The pH ranges of units CU and CF indicate that the colluvial soils underlying the reworked tailings have been acidified. There is generally an increase in soil pH with depth as shown in Figure 5.1, whereas the pH of the tailings showed an opposite trend with increasing depth.

The EC of unit CU ranges from 10,55 - 125,13 mS/m and in unit CF the EC range is 0,88 - 94,87 mS/m. The EC of all the colluvial soil samples is below the threshold value of 400 mS/m

5.4.3 Alluvial soils

The alluvial topsoil unit AU has a pH ranging from strongly acidic to neutral (3,17 - 7,73), but is usually less than 4,50. The alluvial subsoil unit (AL) has a pH ranging from 3,85 - 8,00 but is generally above 7,00. The pH ranges of both the alluvial topsoil and subsoil indicate that the soils have been acidified by the leachate generated in the tailings. The alluvial topsoils, however, are affected to a higher degree, usually displaying lower pH values. There seems to be an increase in soil pH with increasing soil depth (Figure 5.2).

The EC of unit AU ranges from 1,03 - 149,03 mS/m. The EC of the alluvial subsoil (unit AL) ranges from 2,89 mS/m - 200,61 mS/m. All the alluvial soils have EC values below the threshold of 400 mS/m.

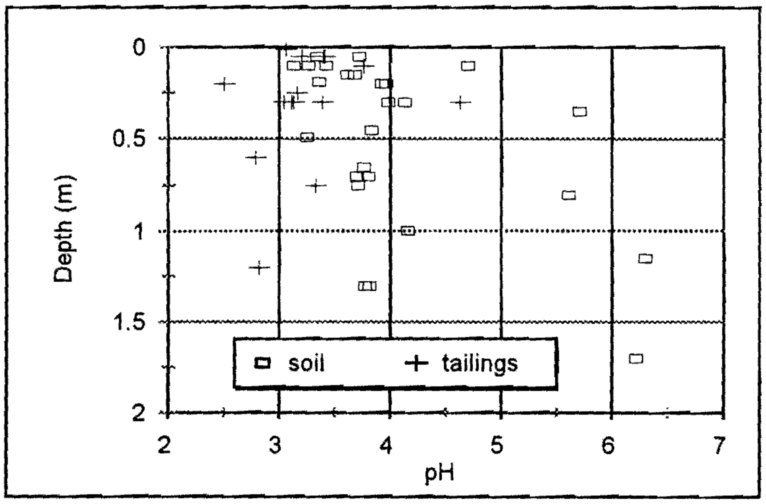

Figure 5.1 Relationship between soil and tailings depth and pH in the colluvial soils.

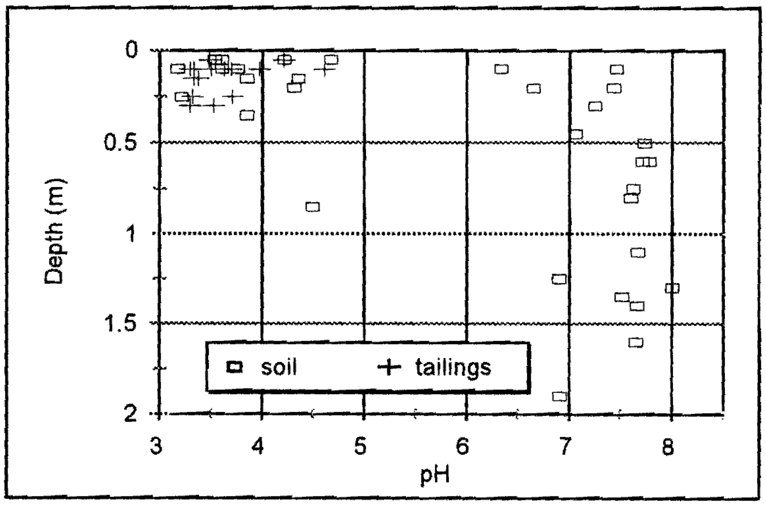

Figure 5.2 Relationship between soil and tailings depth and pH in the alluvial soils

5.5 TRACE ELEMENT SOIL CONTAMINATION

The majority of the soil samples overlain by reworked gold mine tailings show lower pH and higher EC values than found under natural soil conditions. These soils are therefore affected by the overlying tailings. The tailings produces acidic leachate that contains salts and trace elements in solution. The changes in pH will also affect the solubility and bio-availability of elements originally present in the soil. The aim of this portion of Chapter 5 is to investigate if the affected soils show trace element concentrations which are higher than would be expected under natural pedogenic conditions. This would indicate that the soils are contaminated by trace elements originating from the gold mine tailings. This aim is achieved by comparing the total trace element concentrations in the soils to the Dutch ABC threshold concentration values.

5.5.1 Trace element concentrations in the affected soils compared with guideline values

The Dutch ABC system uses a three tier approach to identify if soils or water are contaminated. The first tier concentrations (A-values) are those concentrations below which the soils or water are probably not contaminated. The second tier (B-values) indicate concentrations above which there is a need for further investigation. The last tier (C-values) are those concentration levels above which site clean-up is required, (Moen *et al.*, 1986). Table 5.5 shows the Dutch ABC concentration standards as well as the South African soil quality standards (after Steyn *et al.*, 1996) of the trace elements applicable to the study.

Table 5.5 Dutch ABC guideline concentrations and South African soil standards (mg/kg)

	As	**Co**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
SA standards	2	20	80	100	50	56	185
A - values	20	20	100	50	50	50	200
B - values	30	50	250	100	100	150	500
C - values	50	300	800	500	500	600	3000

The South African soil quality standards are generally lower or equal to the first tier concentration values of the Dutch system. For the purpose of this study the Dutch system is employed to assess the pollution status of the soils, as this tiered system can be used to determine both the degree of pollution and when soil cleanup is considered necessary. The South African system however, can only be used to determine if threshold concentrations are exceeded or not.

5.5.1.1 Tier one analyses (Dutch A - value screening)

The percentage and range of samples in the different soil groups that exceed the first tier Dutch concentrations (DATC values) are shown in Table 5.6. The total concentration of each element in samples from the different soil units was compared with the DATC value. The ratio by which each element exceeds the DATC value was determined by dividing the total element concentration in the sample with the DATC-standard (Table 5.5).

Table 5.6 Frequency (percentage of samples) and range of ratio's by which concentrations of selected elements exceed the Dutch A values (DATC) in the soils and tailings.

ELEMENT		**As**	**Co**	**Cr**	**Cu**	**Ni**	**Zn**
DATC VALUE (mg/kg)		**20**	**20**	**100**	**50**	**50**	**200**
SOIL UNIT	**NUMBER OF SAMPLES**	**FREQUENCY (PERCENTAGE OF SAMPLES THAT EXCEED DATC VALUES) AND RANGE OF RATIO'S BY WHICH DATC VALUES ARE EXCEEDED**					
TC & TA	30	(97%) 1,1 - 16,5	(37%) 1,2 - 4	(100 %) 1 - 5,2	(23%) 1 - 1,4	(53 %) (1 - 4)	(3%) 1,03
CU	11	(82 %) 0 - 4,6	(64%) 0 - 3,5	(91%) 1,5 - 4,1	(55%) 0 - 1,7	(73%) 0 - 3,1	(0 %) -
CF	14	(60 %) 1,1 - 1,5	(47%) 1,1 - 5,3	(100%) 1,3 - 7	(27%) 2,1 - 2,6	(100%) 1 - 6	(0 %) -
AU	16	(81 %) 1,1 - 2	(63 %) 1,1 - 6	(100 %) 1,4 - 2,1	(31 %) 1,1 - 1,7	(100 %) 0 - 4,5	(13 %) 1,3 - 1,5
AL	16	(63 %) 0 - 1,5	(38 %) 0 - 3,5	(100 %) 0 - 2,7	(0 %) -	(100 %) 0 - 4	(13 %) 0 - 1,2

It is evident from Table 5.6 that in unit CU, As, Co, Cr, Cu and Ni usually exceed the screening concentrations. Unit CF has excessive concentrations of As, Cr and Ni. Unit AU has excessive concentrations of As, Co, Cr and Ni, while in unit AL, As, Cr and Ni occur at excessive concentration levels in the majority of samples.

According to the Dutch tiered approach the soils underlying the tailings are most probably contaminated by the elements discussed with each soil unit. Lead concentrations in the affected soils never exceed the screening concentrations while zinc concentrations rarely exceed the screening concentrations in the study area.

5.5.1.2 Tier two screening (Dutch B concentrations)

The Dutch B threshold concentration values (DBTC) were used to establish which elements identified during the tier one analyses should be subjected to further study. The same approach was followed as with the tier one analyses, but the B-value concentrations were used. Lead and Zn concentrations did not exceed the DBTC values of 150 mg/kg and 500 mg/kg respectively, in any of the soil samples and are therefore not shown in Table 5.7.

None of the investigated trace element concentrations exceeded the DBTC values in the alluvial subsoil (unit AL). Arsenic exceeds the threshold concentration of 30 mg/kg in 83 per cent of the tailings samples (units TC and TA) while Cr and Ni occasionally exceed their guideline concentrations. This indicates that the tailings is a source of As and possibly Cr and Ni which should be further investigated. The alluvial topsoil (unit AU) shows occasional concentrations of As, Co and Ni which exceed the DBTC standards. In the colluvial topsoil (unit CU) chromium often exceeds the threshold value and As, Co and Ni occasionally exceed their respective guideline values. In unit CF chromium usually exceeds the DBTC value, while Co, Cu and Ni are occasionally present in elevated concentrations. According to the Dutch A B C system, the tailings and soils should be subjected to further investigation in regard to As, Co, Cr, Cu and Ni.

Table 5.7 Frequency (percentage of samples) and range of ratio's by which concentrations of selected elements exceed the Dutch B (DBTC) values in the soils and tailings.

ELEMENT		**As**	**Co**	**Cr**	**Cu**	**Ni**
DBTC VALUE (mg/kg)		**30**	**50**	**250**	**100**	**100**
SOIL UNIT	**NUMBER OF SAMPLES**	**FREQUENCY (PERCENTAGE OF SAMPLES THAT EXCEED DBTC VALUES) AND RANGE OF RATIO'S BY WHICH DBTC VALUES ARE EXCEEDED**				
TC & TA	30	(83%) 0 - 11	(0 %) -	(20 %) 0 - 2	(0 %) -	7 % (0 - 2)
CU	11	(33 %) 0 - 3	(8%) 1,4	(58%) 0 - 1,6	(0 %) -	(25%) 0 - 1,5
CF	14	(0 %) -	(7%) 2,1	(50%) 0 - 2,8	(28%) 0 - 1,3	(28%) 0 - 3
AU	16	(19%) 0 - 1,3	(19%) 0 - 2,3	(0 %) -	(0 %) -	(12%) 0 - 2,3
AL	16	(0 %) -	(0 %) -	(0 %) -	(0 %) -	(0 %) -

5.5.1.3 Tier three screening (Dutch C concentrations)

If the concentration of a particular element exceeds the Dutch - C value concentration screening levels, it indicates that cleanup of such an element is required at the site. The same approach was followed as with the tier one analyses but the C-value concentrations were used.

Arsenic exceeds the DCTC concentration level of 50 mg/kg in 73 per cent of the tailings samples (units TC and TA) by a range of 0 - 6,6 times the screening concentration. This threshold concentration was also exceeded in sample MT24/2 of unit CU. The other elements all occurred in concentrations below the DCTC screening levels.

5.6 VERTICAL AND LATERAL TRACE ELEMENT CONCENTRATION TRENDS

5.6.1 Vertical concentration trends

Trends in vertical trace element concentrations were investigated by plotting the concentrations of As, Co, Cr, Cu, Ni, Pb and Zn as a function of sample depth and the soil unit from which the sample was obtained (Figure 5.3). Vertical concentration trends for each element are discussed below:

Arsenic

From Figure 5.3 it is clear that there is a distinct pattern in As concentration with depth. The highest As concentrations occur in the tailings units (TC and TA) which overlie the transect. Arsenic concentrations are usually higher than 50 mg/kg in the tailings units. In the underlying soils, As is usually present in concentrations less than 50 mg/kg. There is no distinct difference between As concentrations in the upper alluvial soil (unit AU) and the lower alluvial soils (unit AL). Although the distribution pattern is not distinct, it can be seen that As concentrations in the upper colluvial soils (unit CU) is usually higher than in the underlying unit CF. The lowest As concentrations were measured in the alluvial and colluvial subsoil units AL and CF.

Cobalt

Cobalt concentrations are usually less than 35 mg/kg in the overlying tailings units. The highest Co concentrations occur in the upper alluvial soils (unit AU). Although the distribution patterns are not distinct, it seems that Co concentrations are generally higher in unit AU than in unit AL and that unit AU generally has higher Co concentrations than the upper colluvial soils, unit CU. Somewhat higher Co concentrations occur in unit CU compared with the underlying unit CF, although an anomalously high Co concentration of 106 mg/kg occurs in sample MT18/3.

Chromium

The chromium concentrations in the overlying tailings units vary between 112 and 516 mg/kg and is not distinctly higher than the underlying soils. Somewhat higher Cr concentrations sometimes occur in the underlying alluvial subsoil unit AL compared with the overlying alluvial unit AU. The highest Cr concentrations occur in the colluvial subsoil, unit CF (133 - 700 mg/kg) and Cr concentrations are usually higher in unit CF than in the overlying unit CU. Higher Cr concentrations usually occur in units CU and CF when compared with units AU and AL.

Copper

The Cu concentrations in the tailings vary between 11 - 72 mg/kg and is usually not higher than in the underlying soils. In addition the lowest Cu concentrations in the transect were measured in some of the tailings samples. The upper alluvial soils (unit AU) usually has higher Cu concentrations than the underlying unit AL. Although the highest Cu concentrations were measured in some colluvial subsoils, unit CF does not always have higher Cu concentrations than the overlying unit CU.

Nickel

The Ni concentrations in the overlying tailings are usually lower than in the underlying soils. The Ni concentrations of the overlying alluvial soils (unit AU) are usually higher than the underlying unit AL (except for samples MT13/2 and MT15/3). Similar to Cr and Cu, the highest Ni concentrations were measured in the colluvial subsoils, but from Figure 5.3 it is evident that unit CF does not always have higher Ni concentrations than the overlying unit CU.

Lead

There is generally less Pb in the tailings than in the underlying soils. From Figure 5.3 it can be seen that the Pb concentration in the lower alluvial soils (unit AL) is usually higher than the upper alluvial soils (unit AU). Similar to Cr, Cu and Ni concentrations, the highest Pb concentrations were measured in the colluvial subsoils, but unit CF does not always have higher Pb concentrations than the overlying unit CU.

Zinc

The Zn concentration of the upper alluvial unit (AU) is usually higher than the Zn concentration of the overlying tailings as well as the underlying alluvial subsoil (unit AL). No clear concentration distribution pattern can be observed in the colluvial soils as Zn concentrations in units CU and CF are comparable.

5.6.1.1 Discussion of vertical trace element concentration trends

The vertical concentration trends are summarised below and some of the trends are followed by a short discussion which aims to give reasons for the trends that will be further explored in Chapter 6.

- **Arsenic concentrations in the tailings are usually higher than in the underlying soils.** This indicates that the tailings are a source of As contamination. The As could be insoluble and as a result not be able to leach into the underlying soils.
- **The Cr concentration of unit CF is in general higher than the Cr concentration of the overlying unit CU.** Dissolved chromium present in the soil moisture may be preferentially adsorbed on the Fe and Mn oxides which occur in CF.
- **Concentrations of Co, Cu, Ni and Zn is in general higher in the overlying alluvial unit AU than in the underlying unit AL.**
- **Lead and to a lesser extent Cr have higher concentrations in the underlying unit AL than in the overlying AU.**

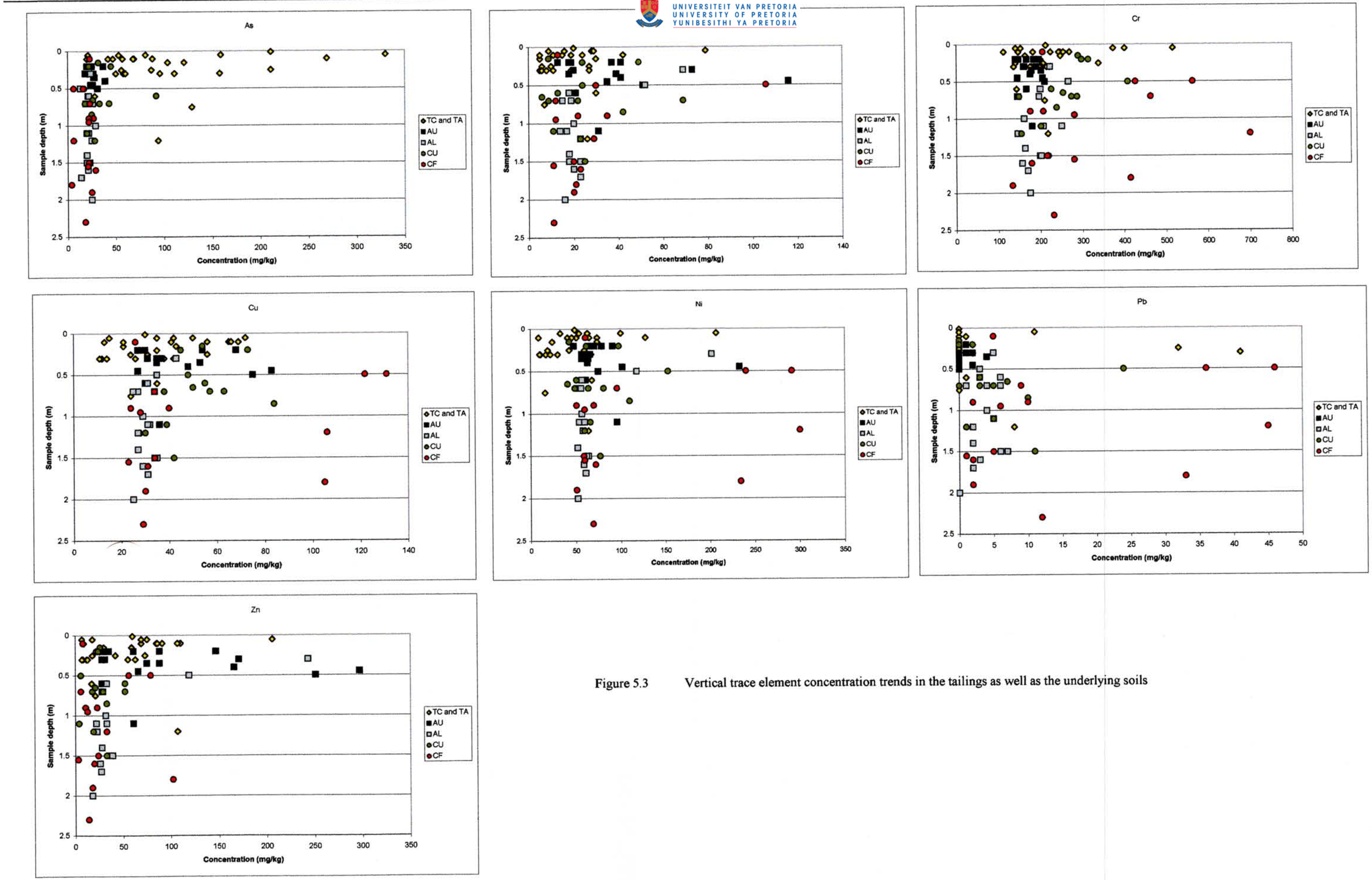

Figure 5.3 Vertical trace element concentration trends in the tailings as well as the underlying soils

5.6.2 Lateral concentration trends

Lateral trends in trace element concentrations were investigated for the transect from test pit MT28, closest to the tailings dams in the north west, to test pit MT1 farthest from the dams and closest to the Kromdraai Spruit in the south east. The lateral trace element concentration trends in the transect are discussed by comparing the trace element concentration in the tailings (units TC and TA) with the trace element concentrations in the soil unit directly underlying the tailings (usually units AU and CU except in test pit MT13 where AL underlies the tailings and MT22 and MT28 where unit CF underlies the tailings) (Refer to Figures 4.1 and 4.2). The vertical dotted lines in Figure 5.4 indicate the area between test pits MT24 and MT23, where the paddocked tailings stop, and pit MT15, at the transition between the colluvial and alluvial soils, respectively. A two test pit moving average was used to decrease scattering and to emphasise any trends. Lateral geochemical trends are discussed separately for each element:

Arsenic

Arsenic concentrations are always higher in the tailings than in the underlying soil. The highest As concentration in the tailings occurs between test pits MT15 and MT16, where the colluvium grades into the alluvium. The highest arsenic concentrations occur in the soils underlying the paddocked tailings (between MT28 and MT25). A slight increase in As concentration, similar to the tailings, occurs between test pits MT15 and MT16, at the contact of the colluvial and alluvial soils.

Cobalt and Nickel

Cobalt and Nickel display similar geochemical trends and are discussed together. Cobalt and Ni concentrations are generally lower in the tailings than in the underlying soil, except in the vicinity of MT15, at the contact of the colluvial and alluvial soils. For both elements an increase in concentration occurs from test pit MT7 towards the Kromdraai Spruit. The lowest Co concentrations in the colluvial soil occur underneath the paddocked tailings, at the contact of the colluvial and alluvial soils and between test pit MT4 and the Kromdraai Spruit. This relationship is not as distinct for Ni. A localised Ni high occurs in the colluvial soil at test pit MT23, adjacent to the paddocked tailings. A similar localised Co high occurs in the colluvial soils at test pit MT21. In general, the highest Co and Ni concentrations in the soil occur in the alluvial topsoil, with a maximum at test pit MT11. A general decrease in Co and Ni concentration is observed along the alluvial transect as the Kromdraai Spruit is approached.

Chromium

Chromium concentrations in the paddocked tailings are usually lower than in the reworked tailings overlying the colluvial soil. The reworked tailings overlying the alluvial soils show an increased Cr concentration between test pit MT7 and the Kromdraai Spruit. The highest Cr concentration in the tailings occurs at the transition of the colluvial soils into the alluvial soils. In the colluvial topsoils the lowest Cr concentration occurs underneath the paddocked tailings while the highest Cr concentration occurs at MT23, underneath the transition between the paddocked and the reworked tailings. The alluvial topsoils usually contain less Cr than the upper colluvial soils and a general decrease in Cr concentration occurs between MT15 and the Kromdraai Spruit.

Copper

The copper concentration in the tailings is usually less than in the underlying soils, except between test pit MT7 and the Kromdraai Spruit. A peak in Cu concentration is present in the tailings at the transition of the colluvial soils into the alluvial soils. In the colluvial soils Cu is usually less (except at MT25) where the upper soils are underlain by paddocked tailings. In the upper alluvial soils there is a general decrease in Cu concentration towards the Kromdraai Spruit. The highest Cu concentration occurs in the alluvial soil at MT11.

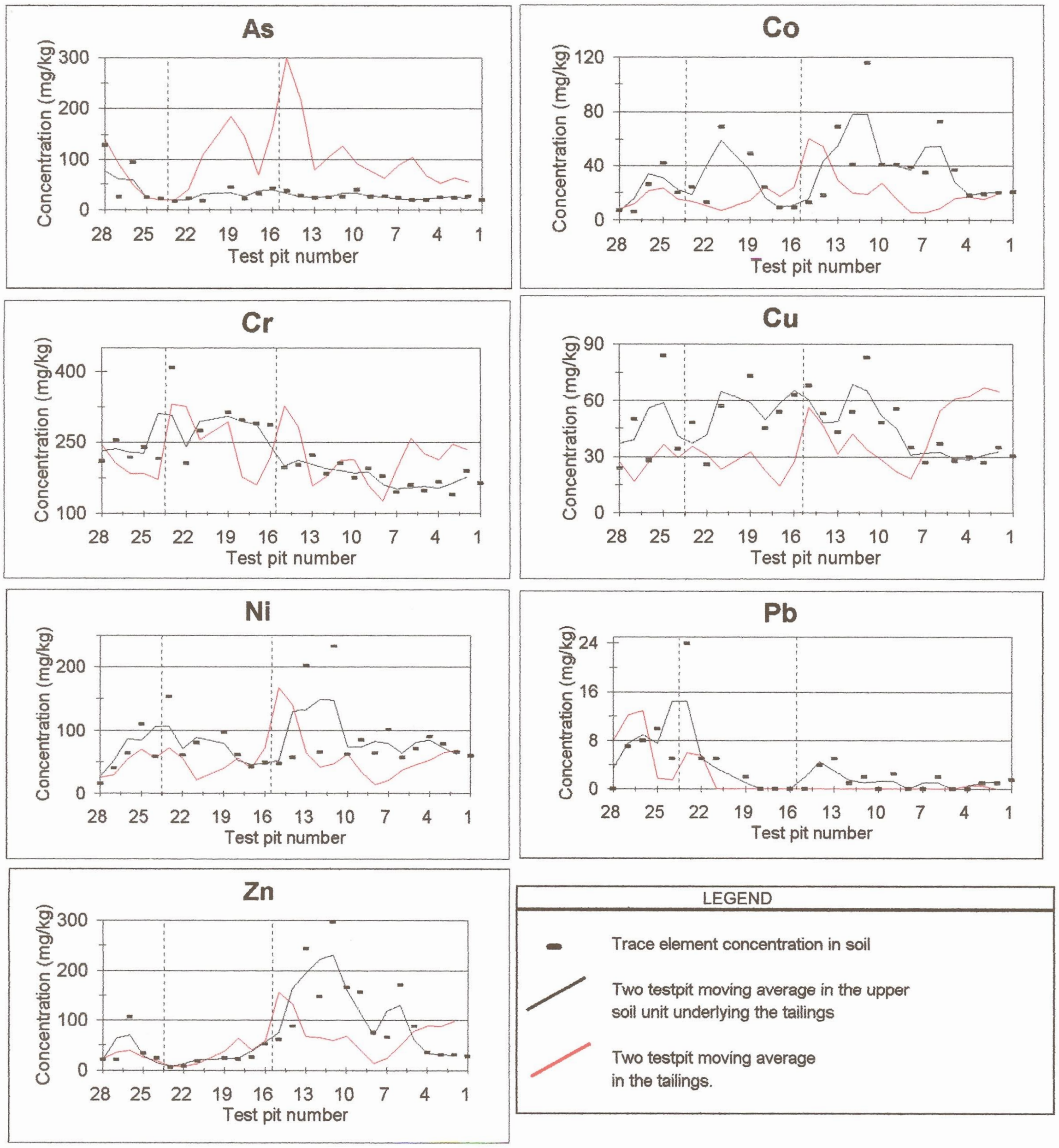

Figure 5.4 Lateral trace element concentration trends in the upper soils and overlying tailings of the investigated transect

Lead

The highest Pb concentrations in the tailings and the soils, occur above the colluvial portion of the transect. In the tailings overlying the colluvial portion of the transect, higher Pb concentrations occur in the paddocked material (MT24 to MT28), while lower Pb concentrations occur in the reworked tailings (MT23 to MT16). In the colluvial soils, a localised Pb high (similar to Cr and Ni) occurs at MT23. The Pb concentration of the upper colluvial soils is in general more than in the alluvial portion of the transect and a general decrease in Pb content is evident in the upper alluvial soils as the Kromdraai Spruit is approached.

Zinc

There is in general less Zn in the tailings than in the underlying soils. Similar to Co, Cu and Ni the highest Zn concentration in the tailings occurs at MT15 where the colluvial soils grade into the alluvial soils. The same increase in element concentration in the tailings is also evident from MT7 towards the Kromdraai Spruit. Zinc concentrations in the colluvial soils are lower than in the alluvial portion of the transect (between MT15 and MT5). Similar to Co, Cu and Ni a localised Zn high occur at MT11.

5.6.2.1 Discussion of lateral trace element concentration trends

The purpose of this section is to summarise lateral trace element concentration trends as observed along the transect in the tailings and the upper portions of the soils underlying the tailings. Some of the trends are followed by a short discussion which aims to give a reasons for the trends that will be further explored in Chapter 6 of this document:

- **In the tailings all the investigated element concentrations except Pb, show a localised high concentration at MT15**. It is at this portion of the transect where the sandy colluvial soils grade into the clayey alluvial soils. Lateral soil moisture movement will reduce as the clayey soils are reached, which may cause soil moisture flow lines to reach the surface. This is an example of the "seepage line" effect that is found in some soil toposequences. Trace elements in solution may then be deposited due to evaporation, causing a localised enrichment in trace element content.

- **In the tailings Co, Cr, Cu, Ni, and Zn show an increase in concentration from MT7 towards the Kromdraai Spruit**. This trend is significant as it shows that higher trace element concentrations occur near the stream, indicating that these elements can enter and affect the surface water environment. This indicates a potential water pollution hazard.
- **In the colluvial portion of the transect Ni, Pb and Cr show high concentrations at MT23, adjacent to the paddocked tailings**.
- **In the alluvial portion of the transect Co, Cu, Ni and Zn show high concentrations at MT11**. This portion of the alluvial transect has a thin vertic A horizon overlying the G-horizon. As the G-horizon has a diagnostically high water content, the observed high element concentrations may be due to evaporation forces which draw water to the A horizon through capillary action. The evaporating water will concentrate dissolved elements in salts which precipitate as the water evaporates, thus enriching the trace element content of the upper soils.

5.7 SUMMARY

INVESTIGATED ELEMENTS

- Of the group of elements determined by the Philips PW 1606 Simultaneous X-ray Fluorescence Spectrometer, only concentrations of As, Co, Cr, Cu, Ni, Pb and Zn were used in the study. These elements, when present in elevated concentrations, have adverse effects on human and livestock health, aquatic ecosystems, crop yield and soil sustainability,.

GOLD MINE TAILINGS AS A SOURCE OF TRACE ELEMENT CONTAMINATION

- The tailings dams of the study area were constructed with slimes produced by milling of ore from the Black Reef Formation. Pyrite was shown to be the principal sulphide mineral in the ore of that formation. Laboratory analyses as well as literature studies show the pyrite to contain high concentrations of As, Ba, Co, Cr, Cu, Ni and Zn. Salts composed of iron-, sodium potassium iron-, aluminum iron-, magnesium-, aluminum- and sodium sulphates precipitate on the tailings due to capillary rise and subsequent evaporation of salt-rich liquids. These salts were demonstrated to have very high water soluble concentrations of As, Cd, Co, Cr, Cu, Ni, Pb and Zn. The tailings are therefore a potential source of trace element pollution.

GOLD MINE TAILINGS IS A SOURCE OF ACIDITY

- It is well known that sulphide-rich gold mine tailings produces acidic leachate due to the oxidation of sulphide minerals in the presence of oxygen and water. The tailings covering the soils in the study area has an average pH of 3,43 indicating that this material produces acidic leachate. These acidic solutions have affected the underlying soils as the pH of the topsoils underlying the tailings are all significantly lower than what would be expected under natural pedological conditions.

SOIL POLLUTION ASSESSMENT

- The acidic leachate produced in the tailings cover, contains dissolved trace elements which will contaminate the soil through which the leachate permeates. In order to assess the extent to which the soils are contaminated by trace elements, the concentrations of As, Co, Cr, Cu, Ni, Pb and Zn in the soil and tailings samples were compared with the Dutch soil quality guidelines.

- According to the Dutch soil quality guidelines the tailings is a potential source of As, Cr and Ni. Unit CU is contaminated with As, Co, Cr and Ni while unit CF has elevated concentrations of Cr, Co, Cu and Ni. Unit AU is contaminated with As, Co and Ni. The alluvial subsoil (unit AL) has no trace elements exceeding guideline concentrations.

- Arsenic was identified as a priority pollutant according to the Dutch-C screening values.

VERTICAL TRACE ELEMENT CONCENTRATION TRENDS

Tailings

Arsenic concentrations in the tailings samples are distinctly higher than in the underlying soils whereas Ni, Pb and to a lesser extent Co and Cu concentrations are usually less in the tailings than in the underlying soils.

Colluvial soils

The Cr concentration of unit CF is in general higher than the Cr concentration of the overlying unit CU. For As and Co there seems to be a general decrease in concentration with depth from unit CU to unit CF. Chromium, Cu, Ni and Pb show the highest concentrations in unit CF, but there is no clear concentration trend regarding unit CU and the underlying CF. The Zn concentrations of units CU and CF are comparable and also show no clear concentration with depth trends.

Alluvial soils

Arsenic concentrations show no clear trends as As concentrations in unit AU are comparable with those in unit AL. Concentrations of Co, Cu, Ni and Zn are in general higher in the overlying unit AU than in the underlying AL. Lead and to a lesser extent Cr have higher concentrations in the underlying unit AL than in the overlying AU.

LATERAL TRACE ELEMENT CONCENTRATION TRENDS

- In the tailings all the investigated element concentrations except Pb, show a localised high concentration at MT15, i.e. at the contact between the sandy colluvial and clayey alluvial soils.
- In the tailings Co, Cr, Cu, Ni, and Zn show an increase in concentration from MT7 towards the Kromdraai Spruit.
- In the colluvial portion of the transect Ni, Pb and Cr show high concentrations at MT23, adjacent to the paddocked tailings.
- In the alluvial portion of the transect Co, Cu, Ni and Zn show high concentrations at MT11, where a thin Vertic A horizon overlies the waterlogged G horizon.