GROUNDWATER AND MINING IN THE BUSHVELD COMPLEX

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ABSTRACT

Water Geosciences Consulting completed a number of groundwater projects for mining companies operating in the Bushveld Complex. The mines are extracting the PGE minerals, which comprise Platinum, Palladium, Rhodium and Gold, together with base metals Copper and Nickel. This article focuses on the description of the aquifer systems associated with the Bushveld Complex's mafic and ultramafic rocks and attempts to characterise the shallow groundwater as well as mine fissure inflows within different geographical settings.

The general aquifer model for the Bushveld Complex comprises a perched, shallow aquifer in the weathered zone underlain by a deeper, semi-confined fractured bedrock aquifer. The weathered aquifer system,, as well as the upper portions of the underlying fractured bedrock aquifer, are partially dewatered in the vicinity of mining operations.

Groundwater inflow rates into shallow mining operations within the weathered aquifer vary significantly depending on the structural setting within which the mines are located. Mine fissure (i.e. groundwater) inflow rates into deeper mining operations are highly variable spatially and can be due to leakage from the shallow weathered aquifer, to inflows along distinct fracture systems tapping into both local and distant sources or to a mixture of these sources.

Mine fissure inflow rates were retrieved from existing mine plans to identify locations of significant historical and recent inflows. The identification of distinct structural regimes/settings for water-bearing fissures enables the prediction thereof and allow for early intervention measures (e.g. sealing of fissures, altering mine production programmes, etc.). Mine fissure inflows are predominantly associated with small-scale faults and minor jointing rather than large-scale regional faults, that were found to be comparatively dry.

Groundwater samples from boreholes as well as the mine fissure inflows were analysed for macro- and trace elements, stable isotopes as well as for radio-active isotopes such as tritium (^3H) and carbon-14.

1. AQUIFER TYPES

Crystalline material, such as the norites and pyroxenites of the Bushveld Complex, comprises of (a) an unweathered and intact rock matrix with negligible matrix porosity and permeability, and (b) planes of discontinuity in the rock matrix, including both faults and joint planes (collectively referred to as fractures). The infiltration and flow of groundwater in such system is controlled by the prevailing complex fracture network and can vary in space and time. Such conditions relate to structurally controlled flow systems. However, these fractures are often in-filled by precipitates from late phase fluids (i.e. vein infill). According to Taylor and Howard (2000), the hydrogeological characteristics of the crystalline rock derive from and are related to long-term, tectonically controlled geomorphic processes.

The following two layer aquifer model conceptualises the Bushveld Complex aquifers at a regional scale:

- A shallow weathered bedrock aquifer system (i.e. intergranular aquifer) which might be laterally connected to alluvial aquifers associated with river systems.
- Deeper fractured bedrock aquifer system.

Shallow Weathered Bedrock and Alluvial Aquifers

A shallow unconfined, phreatic (or water table) aquifer comprising of the saprolite (that formed as a result of intensive and in-situ weathering processes) to saprock (differentially weathered and fractured upper bedrock underlying the saprolite) zones (Fig 1). The soil and saprolite are collectively termed the regolith (Fig. 1). The saprolite and saprock are generally treated as a single weathered aquifer unit, referred to as the weathered overburden, which varies in thickness from 12 to 50m. This differentially weathered overburden can be described as highly weathered, yellowish white to yellowish brown sandy, silty soil derived from the in-situ decomposition of the underlying noritic rocks. The degree/intensity of chemical weathering or more specifically the spatial and depth variations thereof, control the geometry of the shallow weathered aquifer profile.

In the vicinity of river courses, alluvial material overlies or replaces the weathered overburden. The interaction of alluvial aquifers and the river depends, amongst other factors, on the prevailing differences between surface water and

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groundwater levels (the river might lose or gain water from the aquifer), on the presence (and thickness) or lack of clogging, semi-pervious layers in the streambed resulting in an imperfect hydraulic connection as well as on the aquifer properties.

The weathered aquifer, in combination with alluvial aquifers (where present), support most irrigation and domestic water-supply demands in the Bushveld Complex, even in areas which are undermined. The latter fact points towards limited hydraulic interaction with the underlying fractured bedrock aquifer.

Deeper Fractured Bedrock Aquifer

The unweathered and fractured semi-confined bedrock aquifer comprises of fractured norites, anorthosites and pyroxenites underlying the upper weathered aquifer. The intact bedrock matrix has a very low matrix hydraulic conductivity and its effective hydraulic conductivity is determined by fractures and mine voids. Groundwater flows through interconnected fracture systems with the potential of rapid vertical groundwater flow from the weathered overburden (and surface water bodies) to greater depths along interconnected conductive zones.

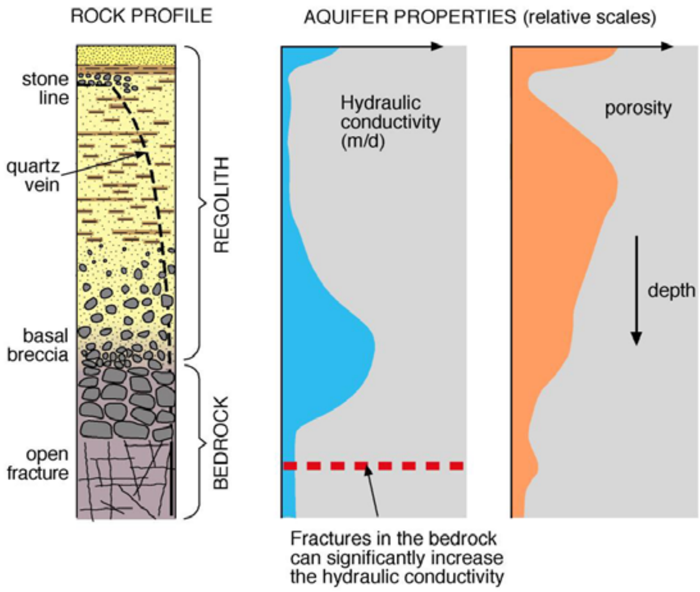

Figure 1. Typical weathered profile for basement rocks
(from Chilton and Foster, 1995 and Taylor and Howard, 2000).

The structural features are extremely variable in nature with regard to frequency, spatial extent, aperture or interconnectedness within the relatively impervious crystalline rock mass. The latter factors account for the observed variable chemical and isotopic signatures obtained for mine fissure inflows in the Bushveld Complex.

2. GROUNDWATER CHEMISTRY

Based on the prevailing aquifer types three dominant water facies are typically encountered in the Bushveld Complex:

- A Mg-Ca-HCO_3 water type for the shallow weathered aquifer which changes towards a very similar Mg-Ca-HCO_3-Cl water facies in the alluvial aquifers along major river systems (e.g. Crocodile River). Impacts of irrigation return flows (i.e. elevated Cl concentrations) are therefore difficult to assess based on the major ion chemistry and the use of isotopes is recommended.
- Water in the deeper fractured bedrock aquifer, as encountered in deeper mine fissure inflows, shows a typical, highly evolved Na-Cl water facies.

Visualisation of the relative mineralization (%-meq/l) in a Piper diagram allows a graphical grouping of groundwater samples (Fig. 2).

Samples from a regional hydrocensus can typically be subdivided into Mg-Ca-HCO_3 or Ca-Mg-Cl water facies, the latter showing higher mineralisation. The dominant Mg-Ca-HCO_3 character of the groundwater samples indicates a recently recharged and shallow groundwater with its chemical character attributed to silicate mineral weathering processes associated with the Bushveld Complex. Samples with Ca-Mg-Cl and Mg-HCO_3-Cl water facies show the highest mineralization, pointing towards irrigation return flows as an additional source of mineralisation. The majority of the hydrocensus groundwater samples, however, get their signature from weathered Bushveld Complex rocks.

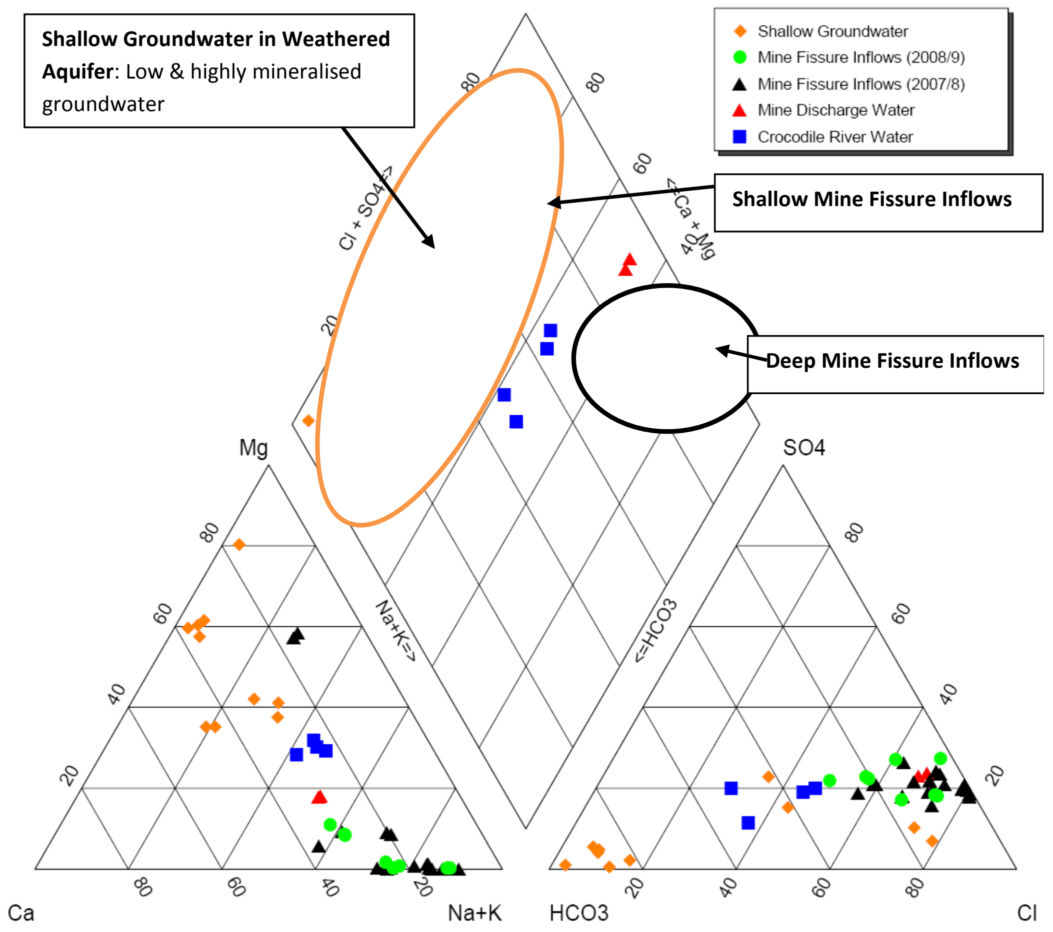

Figure 2. Piper diagram depicting shallow groundwater as well as deep mine fissure inflows.

Some surface water samples present a water type similar to that of the groundwater chemistry, supporting the likelihood of groundwater-surface water interaction.

The deep mine fissure inflows (i.e. groundwater) are typically classified as Na-Ca-Cl or Ca-Na-Cl water facies. The total dissolved solids (TDS) concentrations for the mine inflows present a range of values from 350mg/l to more than 1000 mg/l. The total dissolved solid (TDS) concentrations increase with increasing residence times in the subsurface, i.e. time to equilibrate with the aquifer material. The final mineralisation is then determined by the solubility of dissolved minerals / salts.

The following observations are based on the major ion ratios (Fig. 2):

- Deeper mine fissure inflows are chemically and isotopically different compared to shallow groundwater, including shallow mine inflows, associated with the weathered Bushveld Complex aquifer and groundwater associated with the alluvial aquifer systems.
- Deep mine fissure inflows are fairly uniform in chemical character (i.e. with a dominant Na-Cl water type) compared to the variable chemical character of the shallow groundwater samples and the Crocodile River water.
- The stable isotope ratios and tritium concentrations point to an indirect link between irrigation return flows from alluvial aquifer systems and a considerable number of deep mine fissure inflows.

In conclusion, major ion and stable isotope ratios (i.e. $\delta^{18}O$ and $\delta^{2}H$ ratios) as well as tritium concentrations can be used to differentiate sources for these mine fissure inflows.

3. HYDRAULIC CHARACTERISTICS

Shallow Weathered Bedrock and Alluvial Aquifers

The weathered overburden is considered to have low to moderate transmissivity but high storativity. Gustafson and Krásný (1994) describe such composite or 'near surface' aquifers as approximately uniform, characterized regionally by its mean transmissivity rather than the sporadic fault or fault zones although these are more permeable and extend to great depths.

Numerous pumping tests yielded reasonable and comparable transmissivities of 3 to 8 m^2/d for the weathered bedrock aquifer. However, the determined storativities can vary by several orders of magnitude due to semi-confined conditions in areas overlain by confining layers (e.g. black turf) or semi- to unconfined conditions in localities where these are absent. Typical storativity (S) values range from E-04 to E-03. Selected tested boreholes showed considerably higher transmissivity (T) values of up to 50 m^2/d and the ability to sustain higher pumping rates. For long-term groundwater abstractions around 2 L/s are proposed for these boreholes, while the recommended abstraction rates for most boreholes are approximately 0.5 to 1 L/s. Constructed artificial recharge systems, employing mined-out areas, can support boreholes with even higher yields.

However, much higher transmissivities (T) of up to 500 m^2/d and storativities in the range of 0.15 have been determined for highly transmissive aquifer zones (comprising the shallow weathered and deeper fractured aquifer) within the Bushveld Complex.

Deeper Fractured Bedrock Aquifer

The underlying solid and unweathered crystalline rocks are generally characterized by very low porosity and high hydraulic conductivity values if fractures are intersected. Water is generally stored and transmitted in fractures and fissures within a relatively impermeable matrix. Fractured crystalline rocks are characterized, according to Gustafson and Krásný (1994), by extreme heterogeneity in their hydraulic properties and the hydraulic conductivity can vary, within the same rock mass, by orders of magnitude and over short distances. This structurally controlled heterogeneity and the typical scarcity of sufficient deep boreholes renders regional estimates of aquifer properties difficult. However, regional conductivity values in the range of E-03 to E-01, with higher conductivities assigned to fault zones, yielded satisfactory calibrations of regional numerical models.

4. CASE STUDIES – MINING IN THE BUSHVELD COMPLEX ROCKS

The following case studies give examples of the heterogeneity and variability of Bushveld Complex aquifers and the groundwater chemistry as a function of the structural and geographical setting.

Mining in the Brits Graben

Massive groundwater inflows were experienced in a shallow mining operation (i.e. declines extending to a vertical depth of approximately 25m below ground level) within the weathered bedrock aquifer in the Brits area. The groundwater inflows are related to the structural setting of the declines within the Brits Graben system.

The declines are located in a highly weathered shallow bedrock aquifer bounded by two closely spaced regional NNW-NW striking graben faults with intense synthetic faulting connecting the regional faults. A highly transmissive zone at the interface between the weathered overburden tand the fractured bedrock yielded large quantities of groundwater during drilling. This zone varies in vertical thickness between 12m to 18m and may be thicker when intersected and/or underlain by fracture systems.

An average transmissivity (T) of 285 m^2/d or an average hydraulic conductivity (k) of 5.7 m/d (if a thickness of 50 m is assumed) was determined with the long-term pumping tests. A numerical groundwater model presented lower transmissivity (T = 40 m^2/d) and hydraulic conductivity (k = 2 m/d) values due to averaging these parameters over the entire aquifer system(s). No consistent storativities could be determined using the analytical models, literature values for weathered norites or numerically determined values. Analytical solutions calculated considerably high storativities in the range of E-01, while a well calibrated transient groundwater model presented storativity values in the range of E-03 for the entire model domain. The fast recovery of the boreholes after the pumping receded showed that a highly transmissive aquifer zone extends beyond the dewatered area or is replenished by another source (e.g. a major fault or a surface water body), though no leakage from a so-called recharge boundary was apparent in the drawdown curves.

The long-term pumping tests showed a very slow decline of water levels. Due to the generally high ratio of transmissivity to storativity (i.e. the hydraulic diffusivity) a fast, wide and shallow spread of the cone of depression can be expected. The encountering of no-flow boundaries (e.g. regional faults) after 1000 and 6500 minutes of pumping, indicates a large but potentially limited extent of the high yielding aquifer area. Though dewatering of the high yielding aquifer area is therefore deemed possible (and was calculated with numerical model runs), the required high pumping rates as well as the regional extent and subsequent impact of the cone of depression (of the water table) on other water users will be considerable.

Significant shallow groundwater inflows occurred and delayed the recent re-development of the declines. These high yielding aquifer zones pose a technical challenge and potential economical risk to future mining development in the area, that have to cope with massive and probably sustained groundwater influxes.

In contrast, underground mining operations to depths of 200m below surface on the edges of the Brits Graben system are well established and do not face similar challenges.

Open Cast Mining in the Steelpoort Valley

The Steelpoort area is relatively dry with a significant shortage of water for mine processes. Apart from the already almost fully allocated local surface water resources (including the adjacent Steelpoort River), a substantial but widely dispersed allocatable groundwater resource exists. Although the regional Steelpoort Fault runs along the valley, there is no evidence of significant groundwater yields associated with the fault.

Groundwater in the Steelpoort Valley occurs mostly in the upper weathered and fractured zone of the Bushveld Complex rocks, as well as in alluvium associated with perennial and ephemeral rivers. These aquifers vary greatly in thickness, extent, and hydraulic properties. They are also affected by linear features such as dykes, joints, fractures and zones of mineralization. Most boreholes in the area yield less than 2 L/s. Boreholes with anomalous yields of 10 L/s or higher exist and are thought to be associated with the alluvium in ephemeral drainages. In general, very little groundwater is found in the deeper, unweathered part of the Bushveld Complex rocks. The Steelpoort River is sustained by shallow groundwater flow and gains water throughout most of the study area.

Open Cast Mining in the Marikana Area

Relatively low groundwater inflow volumes into an open cast mining operation were anticipated for the Marikana area based on the structural setting and results of pumping tests targeting mostly the shallow weathered aquifer. However, long-term, average groundwater inflows of approximately 30 L/s (as predicted by a calibrated numerical groundwater model) into the proposed 5km long open pit may be an underestimate if compared to current observed inflows during the initial stages of mining.

Groundwater inflow volumes into the open pit are generally difficult to predict initially based on the following:

- Distinct fracture systems / zones may contribute to the majority of groundwater inflow volumes.
- A larger volume of the aquifer is accessed through continuous mine development promoting increasing groundwater inflows into the open pit.
- The ability of the aquifer material to both transmit and store groundwater is significantly increased in the vicinity of the open pit during mining activities (e.g. unloading of rock masses and blasting activities).

However, the long-term, average groundwater inflow rates (subject to seasonal and long-term climatic variations) into the full extent open pit will stabilise due to the limited capacity of the surrounding aquifer system to support the inflows. Only ongoing monitoring of abstraction from the open pit will accurately verify the groundwater inflow rates.

Deep Mining in the Thabazimbi Area

Mine fissure inflow rates into deeper mining operations are highly variable spatially and are related to direct and indirect recharge within the mining area through precipitation, return flows from alluvial aquifer systems, irrigation schemes as well as mine discharges. Groundwater recharged further away reaches the mine workings through regional and interconnected fracture systems, contributing to a mixture of the varied inflow sources.

The weathering of silicate and ferromagnesian minerals within the Bushveld Complex rocks is a likely source of mineralization. The dominant Na-Cl water facies for the mine fissure inflows indicate relatively old groundwater with longer residence times (i.e. distances travelled through the Bushveld Complex) or may represent irrigation return flows from alluvial aquifer systems with higher sodium (Na^+) and chloride (Cl^-) concentrations due to evaporation effects.

Due to mine dewatering the local groundwater flow directions in the deeper fractured bedrock aquifer are generally re-directed towards the mine. This results in locally different groundwater flow directions for the upper weathered (including alluvial) and deeper fractured aquifer systems. In addition, the upper weathered aquifer is gradually drained within the area affected by mine dewatering except where localized surface sources of water (i.e. rivers, tailing dams, discharge ponds) exist.

Distinct groupings for the deeper mine fissure inflows are evident in various diagnostic plots, such as the Na-Cl cross-plot (Fig. 3) and Durov diagram. Based on major ion and stable isotope (i.e. $\delta^{18}O$ and $\delta^{2}H$) ratios, varied sources for the mine fissure inflows (although dominated by a distinctive Na-Cl water type) have been identified (Fig.'s 3 and 4):

- Relatively low mineralised, shallow groundwater from the weathered bedrock and alluvial aquifer systems. The groundwater is characterised by enriched $\delta^{18}O$ and $\delta^{2}H$ isotope signatures.
- Deep mine fissure inflows in the western part of the mine associated with the Bushveld Complex – Relatively lower mineralised (TDS ≈ 450 mg/l) older groundwater with apparent radiocarbon ages of approximately 3900 ± 40BP. These mine fissure inflows are characterized by depleted stable ($\delta^{18}O$ and $\delta^{2}H$) isotope ratios and fairly low tritium concentrations (< 1 T.U.'s) compared to Crocodile River water (> 10 T.U.'s). The isotope ratios indicate direct recharge by precipitation with minor evaporation losses prior to infiltration.The Bushveld Complex support a constant inflow with evidence of massive mine fissure inflows (i.e. estimated at 3 to 5 ML/day) associated with the NNW-NW striking faults.

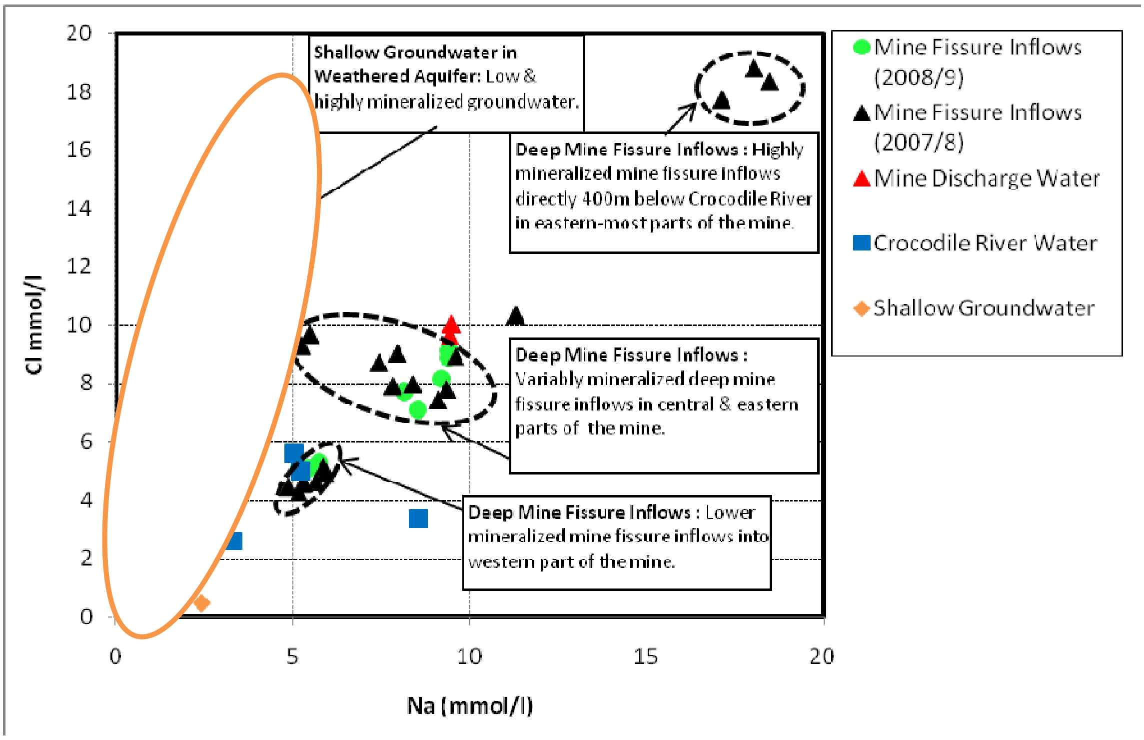

Figure 3. Chloride (Cl^-) versus sodium (Na^+) plot for mine fissure inflows as well as groundwater from the weathered bedrock and alluvial aquifer systems.

- Deep mine fissure inflows of mixed origin in the central and eastern parts of the mine - Relatively higher mineralised (TDS ≈ 700 - 1000 mg/l) groundwater with variable but relatively enriched stable isotope ($\delta^{18}O$ and $\delta^{2}H$) ratios and higher tritium concentrations (4 - 6 T.U.'s), compared to the Bushveld Complex groundwater, indicating relatively younger (or recent) groundwater. The higher tritium concentrations combined with the enriched stable isotope ratios for the mine fissure inflows point to a mixture of groundwater associated with alluvial aquifer and groundwater within the Bushveld Complex. Massive mine fissure inflows are recorded associated with NNW-NW striking faults.
- Deep mine fissure inflows in the eastern-most part of the mine possibly link to buried, off-channel alluvial deposits underlain by faulting - Highly mineralised (TDS ≈ 1400 mg/l) groundwater with depleted stable isotope signatures and relatively lower tritium concentrations (< 1.5 T.U.'s) compared to the Crocodile River water (> 10 T.U.'s). The depleted stable isotope ratios indicate direct recharge by precipitation or water subjected to slight evaporation processes prior to infiltration. Major ion ratios, stable isotope ratios as well as a comparison of tritium concentrations indicate that there is no direct hydraulic link between the Crocodile River and the mine fissure inflows approximately 400m below the Crocodile River. These sustained (≈ 0.3 to 0.5 ML/day) fracture controlled inflows may be associated with the Crocodile River fault and/or inflows from deep and buried off-channel basins, underlain by faults, within the extensive alluvial plains east of the Crocodile River.
- The mine discharge water (Fig's 2, 3 and 4) is thus a mixture of all mine fissure inflows with varied geochemical and isotopic signatures.

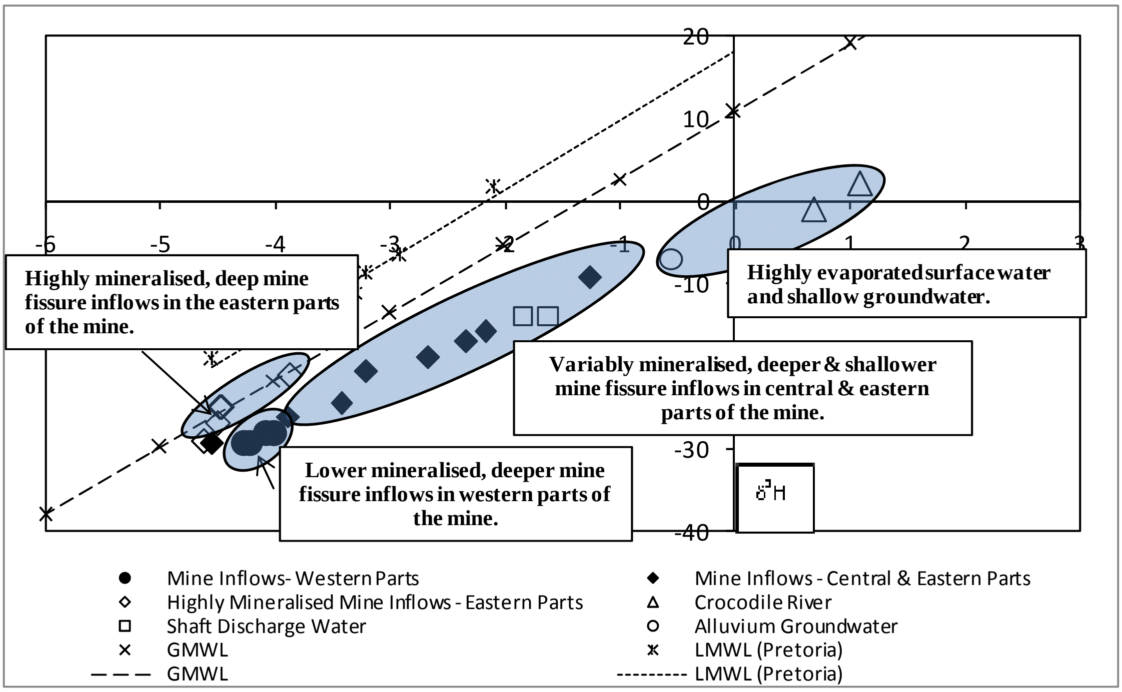

Figure 4. Isotopic compositions for mine fissure inflows and shaft discharge water, groundwater in the alluvium aquifer, Crocodile River water and the global and local meteoric water lines plotted on a δ^2H versus δ^{18}O diagram.

The variable major ion ratios, stable isotope ratios (i.e. δ^{18}O and δ^2H ratios) and tritium concentrations for the mine fissure inflows indicate that different sources exist for these inflows. The following observations are based on the major ion and isotope ratios:

- The deeper mine fissure inflows are chemically and isotopically different compared to shallow groundwater, including shallow mine inflows, within the weathered Bushveld Complex aquifer and groundwater associated with the alluvial aquifer systems.
- The deeper mine fissure inflows are fairly uniform in chemical character (i.e. a dominant Na-Cl water type as an end-member of water evolution) compared to the variable chemical character of the shallow groundwater samples
- The stable isotope ratios and tritium concentrations point often to an indirect link between irrigation return flows (originating from alluvial aquifer systems) and a considerable number of deep mine fissure inflows.

The absence of significant mine fissure inflows associated with large-scale regional fault systems suggests that these faults are preferentially drained due to their high permeability compared to the groundwater retention capacity of the surrounding fractured rock mass. As a result, steeply-dipping striking, smaller-scale faults and jointing within the rock mass are water-bearing with sustained or temporary inflows when intercepted by mine workings.

5. REFERENCES

Chilton, P. J., and Foster, S. S. D. (1995). "Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa". *Hydrologeology Journal*, *Vol. 3*, *No. 1*. 36-49.

Gustafson, G. and Krasny, J. (1994). Crystalline rock aquifers: Their occurrences, use and importance. *Applied Hydrogeology*. *Vol. 2*. *Issue 2*, 64- 75.

Taylor, R. and Howard, K.. (2000). A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda. *Hydrogeology Journal, 8,* 279 – 294.