Approfondissement du modèle conceptuel hydrogéologique des systèmes aquifères fracturés. Kempfield,SE Australia
Refinement of conceptual groundwater model for fractured aquifer system, Kempfield, SE Australia

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I. ABSTRACT

A conceptual model for groundwater flow through a complex metamorphic-sedimentary fractured rock with major lineaments has been revised on the basis of new hydrogeological and isotope data. Previous investigations of an aquifer system at Kempfield, SE Australia focused on potential dewatering and water supply requirements. Additional core drilling and geophysical survey data have confirmed and refined the existence of two major lineament structures steeply dipping and extending N-NE (80 degree dip to the west) and W-NW with subvertical dip. Continued water quality and stable isotope ($\delta^{18}O$ and $\delta^{2}H$) analysis have enabled further delineation of previously identified fracture zones which were crosscutting and longitudinal to base metals mineralisation. Pore pressure measurements of deep fractured rock and shallow weathered zones have enabled the calculation of vertical gradients and offered alternative recharge infiltration pattern. The result of additional investigations have shown that the major W-NW lineament is a superior conduit for groundwater flow based on the presence of broken quartz and clay infill within the stress related open joints. This is further confirmed by two distinct water types $Cl+SO_4$ –Ca+Mg and HCO_3 –Na+K and presence of artesian conditions. Stable isotope data for groundwater plots in four clusters which correlate with lineaments and basement zone. All groundwater data plots along the local meteoric water line confirming meteoric groundwater origin, however the pore pressure data imply that weathered zone is separated from deep fractured aquifer. This paper demonstrates the importance of ongoing data collection and interpretation in re-defining and improving a conceptual model of a fractured rock aquifer.

II. INTRODUCTION

The current hydrogeological conceptual model for the Kempfield fractured rock aquifer is based on the drilling and testing results demonstrating that flow and chemistry of the aquifer system are strongly dependent on presence and characteristics of the fracture zones and major lineaments. This confirms the basic assumption by others (Cook *et al*, 2006 ; Oxtobee and Novakowski , 2002) that fractured rock hydrostratigraphic unit cannot be simply represented by porous media. Furthermore, Novakowski (2007) found that limited knowledge of fractures for a given system can result in significant overestimation of recharge to the aquifer, which means that the detailed knowledge of fractures within such system can improve our understanding. A detailed multidisciplinary approach is considered important to refine and confirm the accuracy of the initially developed conceptual model (David *et al*, 2014).
The objective of this study is to refine and produce the comprehensive conceptual model in a complex structurally controlled metasediment complex. The investigation includes detailed review and mapping of the drill cores in particular defining the fractures, review of long term groundwater level data, investigation of vertical gradients between the weathered overburden and fractured rock

hydrostratigraphic unit, temporal and spatial trend in geochemical analysis of major ions and stable isotopes of water $\delta^{18}O$ and $\delta^{2}H$ of surface and groundwater.

III. SITE GEOLOGY AND HYDROGEOLOGY

The Kempfield locality is situated in the Hill End Trough, one of the several intracratonic basins developed during Silurian–Devonian in the eastern province of the Lachlan Orogen, Eastern Australia. The oldest basement rocks comprise deep water sediments and andensitic volcanics intrud (Figure 1). Deep water sediments were metamorphosed into black carbonaceous shale. Volcanoclastics and sediments of the basin sequence are unconformably overlying Ordovican basement rocks. The basin sequence has undergone mid-green-schist metamorphic facies with a northeast trending, steeply dipping, metamorphic cleavage which occurs throughout the Hill End Trough terrain. This sequence hosts polymetalic mineralisation.

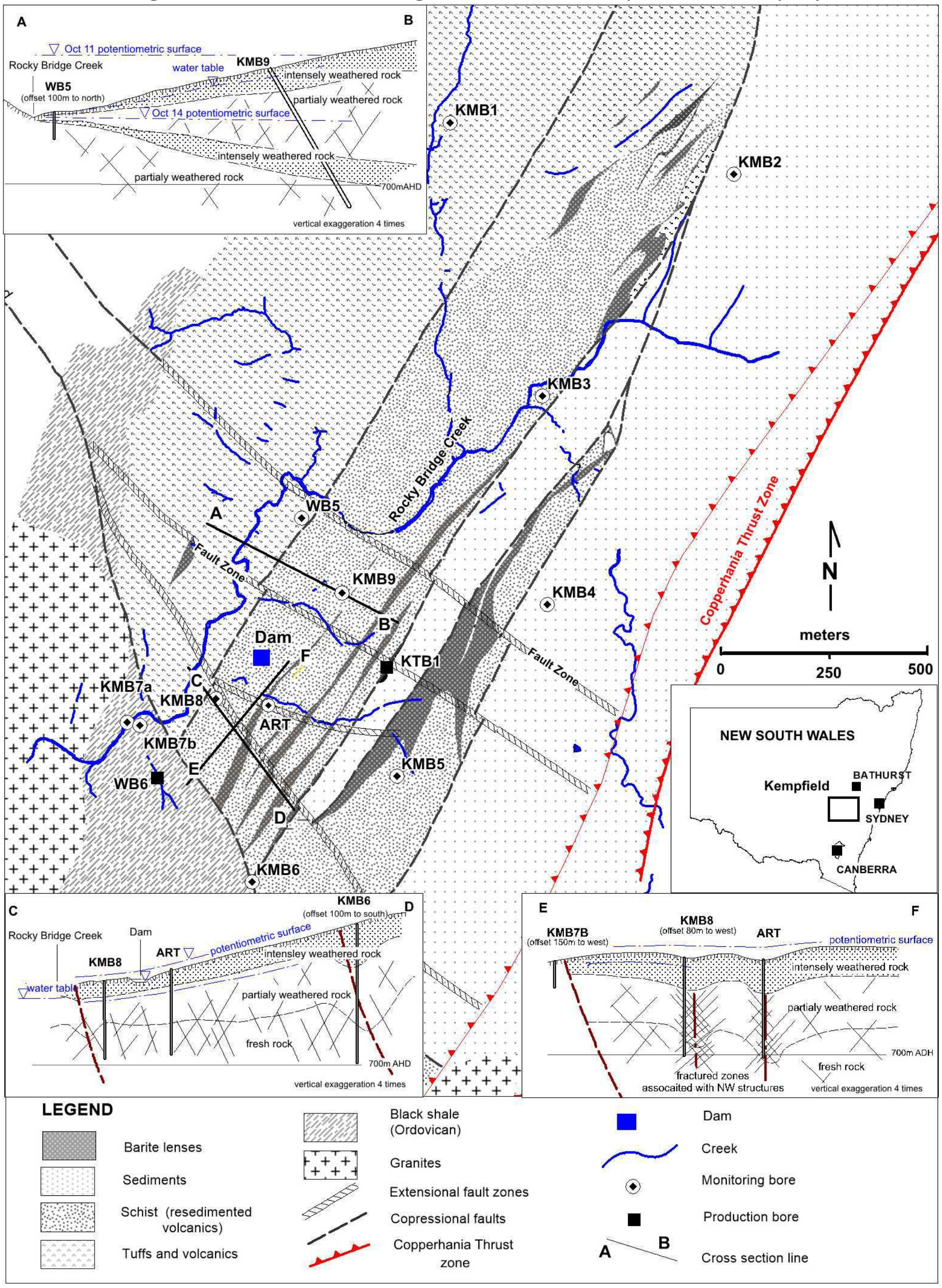

Figure 1– Geology map with piezometer locations and selected cross-sections

As a consequence of compression the basin infill sequence is inverted, tilted and faulted against Ordovician basement along the major thrust system called Copperhania Thrust which controls structural pattern in the Kempfield area. The main structural pattern is characterised with NE trending faults offset by NW trending faults (Figure 1). The NE trending faults are steeply dipping normal faults, and have a compressional character. The NW trending faults were developed parallel with main compressional direction to accommodate displacement on Copperhania Thrust and NE trending faults. These faults are interpreted to be vertical with dip-slip and left-lateral sense of movement and have an extensional nature.
The conceptual understanding suggests that the productive fractured rock zones are a combination of sub-vertical features (believed to be aligned with the major lineaments), and/or probably a more horizontal feature at greater depth at some locations (notably bore KMB8). Within this system hydraulic information only cannot explain the nature and characteristics of groundwater flow. Weathered zone comprising mainly clays, occurs across the site, with its thickness decreasing toward the elevated and low laying areas. This unit is underlain by partially weathered unit which is characterised by altered fresh rock. Due to intense structural deformation of this area, an intensely weathered zone underlays the partially weathered zone in places (Figure 2).

IV. METHODOLOGY

Groundwater monitoring was undertaken in most bores across the site over the period from 2011 to 2015, with eight monitoring campaigns undertaken. The new dataset includes the following:

- Additional exploration drilling program with detailed mapping of weathered and fractured zones and classification of fractures based on their infill and aperture ;
- Water level monitoring in site bores ;
- Continuous pore pressure monitoring for assessment of vertical gradients between weathered and partially weathered unit ;
- Water quality sampling to expand on the previous findings which indicated two distinct water types
- Stable isotope sampling over two distinct climatic periods -spring and summer.

The aim of the additional geology mapping and groundwater sampling was undertaken to improve the understanding of the geochemical signatures of groundwater, to provide understanding into recharge and discharge of the complex metamorphic system, measure the water stable isotopes $\delta^{18}O$ and $\delta^{2}H$ and to conceptualise the structures that characterise this system.
Groundwater samples were collected by micropurging, and were field filtered using 45 µm filter. Field parameters (pH, temperature and electrical conductivity (EC) were measured upon collection using hand held water quality meter (Hydrolab Quanta)). The samples were kept in the cool storage and delivered to accredited Australian Laboratory Services (ALS) laboratory within parameter holding time. Standard techniques were used for analysis, alkalinity by titration, chloride and sulphate by discrete analyser and cations by ICP-MS technique.
Stable isotope samples were collected on two occasions in spring 2014 and summer 2015, and the analysis carried out using Picarro L1115 (Cavity Ring-down Spectrometry) analyser at UNSW Australia laboratory. Reproducibility and accuracy of the analyser is 0.4‰ for δ18O and 4‰ for $\delta^{2}H$. Four Australian Nuclear Science and Technology Organisation (ANSTO) standards and an international standard (Vienna Standard Mean Ocean Water, VSMOW) were used for calibration during water isotope analysis.
Detailed geological mapping was undertaken on the diamond drilled core from ten additional exploration holes drilled since 2012. The following was noted: the frequency, aperture, roughness of fracture wall and infill of the fracture material.
Groundwater levels were measured in 12 site piezometers on a monthly basis (Figure 1), with a data gap in the first half of 2013. In addition, a set of two vibrating wire piezometers installed and fully grouted in the KMB9 borehole at two different elevations (intensely and partially weathered unit) were continuously monitored for the hydraulic head difference in weathered and partially weathered zone.

V. RESULTS

V. 1 Geology mapping

The results from additional drilling program (lithology logs and description of fracturing) were entered in database held by Argent Minerals. The results of this interpretation are given in geology cross-sections (Figure 1). Four zones were identified related to structural deformation and weathering process (Figure 2):

- surficial weathered zone- weathering caused by environmental influence, resulting in oxidised , completely weathered horizon, thickness 10-15m ;
- partially weathered zone – deeper zone with less environmental impact, where chlorite alteration resulted in rock decomposition and development of clays, varying thickness 20 to 30m ;
- deep weathered zone – weathering originated during deposition , hydrothermally altered to clays, varying thickness 5 to 30 m ;
- fresh rock, exposed at high elevations where compressional stresses have resulted in opening of fractures, lacking weathered horizon or if present very thin (up to 1 m).

Logging of fractures and fracture zones along the drill holes, resulted in differentiation between two major fracture types :

- fractures associated with open faults/faults zones, NW-SE extending – derived as a result of extension and characterised by open fractures , 5 to 10 mm aperture, with rough fracture walls and clean quartz infill (Figure 2a)
- fractures/fracture zones association with compressional environment, closed fractures , <2mm in aperture, smooth walls and chlorite and clay infill (Figure 2b).

First set of fractures represent conduit for groundwater flow as evidenced by high yields obtained from WB5 and KMB7B. Second set of fractures and lineaments does not allow groundwater flow through fractures, however based on the interpreted groundwater flow map and geochemical signature upgradient and downgradient, these features are not strictly barriers.

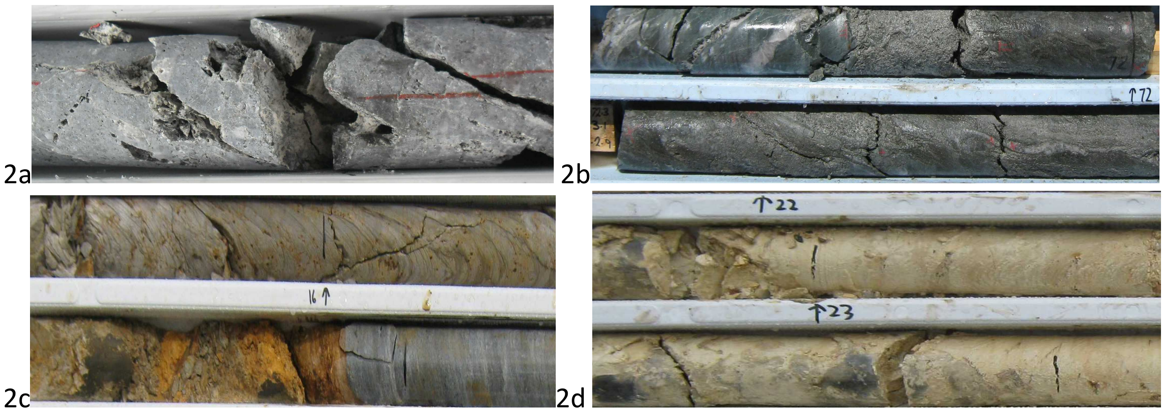

Figure 2 – Fractured rock with open fractures (2a), closed infilled fractures (2b), partially (2c) and intensely weathered rock (2d)

V. 2 Groundwater heads and flow

Regional groundwater flow within fractured rock unit is from the east (813 m Australian height datum (AHD)) to the west with the lowest level at the Rocky Bridge Creek in the west (735 mAHD). Interpreted groundwater contours are distorted in the areas where NW-SE faults cross cut the area. At these locations the gradient decreases indicating that flow is occurring along the fault boundary.

Temporal variations in hydrographs (Figure 3) show different response in bores located away from the fault zones (KMB3 and KMB4) with up to 2 m change in head over time. Piezometers located close to the fault zones (KMB8 and WB5) tend to have greater potentiometric surface fluctuation up to 5.8 m. Rainfall residual mass represents a difference between total monthly rainfall and long term average for a particular month. This provides a difference in rainfall over time, therefore in wetter periods the RRM remains positive and in drier periods it becomes negative. Groundwater hydrographs for piezometers located close to the water transmitting faults show some response to rainfall recharge although with a significant time lag (6 months). At other locations piezometers in fractured rock unit show minor change in potentiometric pressures with rainfall recharge (KMB4). Vibrating wire piezometer (KMB9) has pressure sensors installed in partially weathered and intensely weathered unit. In 2011 the pressure in the partially weathered unit is above the surface, indicating artesian conditions. However there is a decrease in pressure with time, being a result of combined lack of recharge and downgradient artesian drillholes left open resulting in continuous discharge.

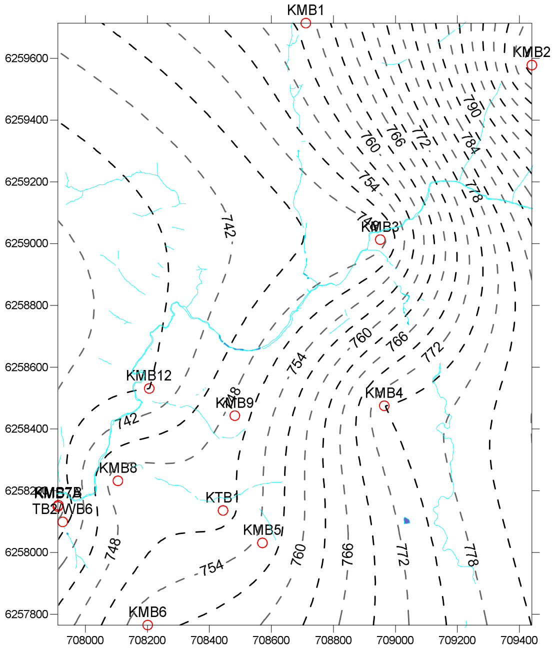

Figure 3 – Interpreted groundwater contours in fractured rock unit, and selected hydrographs for piezometers and vibrating wire piezometers

During the same period sensor in intensely weathered unit shows an increase in water level with a time lag of around several months and a direct pressure response peak coinciding with a significant rainfall event in March 2012 (180 mm in three days).

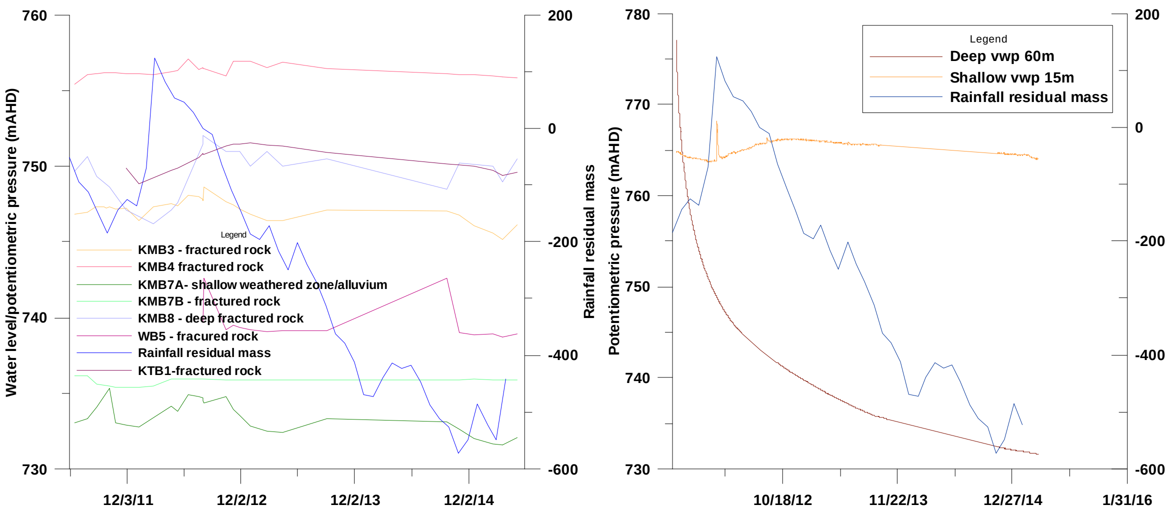

Figure 3 –Selected hydrographs for piezometers and vibrating wire piezometers

V. 3 Hydrogeochemistry

Over time the measured EC values remained stable and in June and December 2014 the average across most sampling locations was just under 1000 µS/cm. The exceptions are KMB7A, KMB7B and KMB8 which have higher EC from 1100 to 1400 µS/cm. Upgradient piezometers (KMB1-KMB4) have average EC varying

from 330-800 µS/cm, piezometers along the compressional faults have EC in the range from 440-800 µS/cm, and the piezometers along the main water conducting faults have slightly higher EC with the average EC from 600-1150 µS/cm. Groundwater pH was natural to alkaline at all piezometer sites.
Figure 5 shows spatial variation in groundwater samples. Sampled groundwaters can be divided into two major groups based on the dominant anion: Ca-Mg-Na-HCO_3 and Ca-Mg-Na-SO_4. The occurrence of sulphate dominated samples coincides with the major metal (Pb, Ba and Zn) mineralisation zones, while bicarbonate samples are found outside of this zone. In addition, four hydrochemical facies can be differentiated: 1) along NW-SE fault zone Mg- SO_4, 2) fractured rock (shale) Na- HCO_3, 3) groundwater in the vicinity of compressional faults Mg- HCO_3 and 4) upgradient groundwater which is mixed. S speciation calculations by PHREEQEC (Parkhurst and Appelo, 1999) indicated that groundwater is undersaturated with respect to gypsum. Ca-Mg-HCO_3 waters are typically produced by dissolution of carbonate minerals calcite and dolomite (Hem, 1985). Both calcite and dolomite are present within schist occurring in bands as a result of hydrothermal alterations and as layers deposited during sediment deposition. In bicarbonate dominated water in order for the calcite and dolomite dissolution to progress carbon dioxide is required The source of CO_2 is most likely shallow zone where CO_2 is dissolved by recharge water. Therefore, for Ca-Mg-HCO_3 to form there must be a connection between shallow and deep zones. Such a connection is not evident from the hydrographs, where shallow weathered zone is hydraulically separated from the deeper fractured rock unit. Groundwater from both weathered and fresh shale (KMB7A and 7B) typically has the lowest SO_4 content compared to other groundwater samples, this being the result of sulphate reduction by bacteria and accompanied by strong presence of H_2S. Ca-Mg- SO_4 water contains higher concentrations of TDS, Ca, Mg and SO_4 and is most likely a result of dissolution of carbonate minerals with sulphuric acid generated by oxidation of pyrite. The origin of Na- HCO_3 water can be from Ca-Mg-HCO_3 by cation exchange on clay minerals. This is confirmed by absence of correlation between Na and Cl , due to cation exchange (Chapelle and Knoble, 1983). Lesney (1992) found that this is typical water composition for shales and siltstones, which agrees well with KMB7A and 7B.

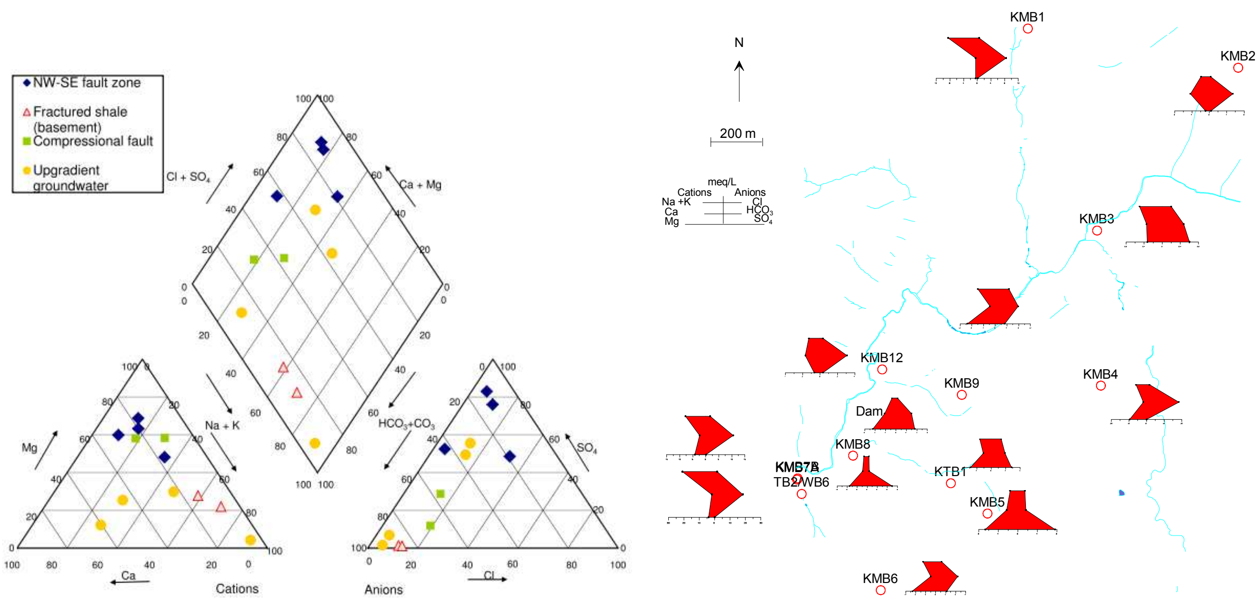

Figure 5 – Groundwater composition shown on Piper diagram (left) and Stiff diagram (right)

V. 4 Stable isotopes

The groundwater samples present an isotopic composition ranging from -8.5‰ to -3.5 ‰ for $\delta^{18}O$ and -50.5‰ to -27.2‰ δ^2H. The surface water sample had 1.1% $\delta^{18}O$ and 1.6‰ δ^2H. Figure 6 shows small seasonal variation in $\delta^{18}O$ and δ^2H between samples collected in spring and summer. Data has been plotted on the local meteoric water line (Hughes and Crawford, 2013) obtained from Lithgow station located 80km east of the site and at the similar elevation. Surface water sample and groundwater sample collected from the dam show the heavier isotopic composition than groundwater samples. Groundwater samples typically plot along the LMWL indicating recent rainfall origin. Some changes in variation in the groundwater signature are natural variations in the isotopic composition of rainfall, mixing with groundwater and evaporation during flow through unsaturated zone (Kendall and McDonnell, 1998). The groundwater isotopic composition is more negative than the rainfall weighted average due to higher altitude of recharge and lower temperatures. Samples collected from the discharge zone (KMB7A, KMB7B, KMB12) have more negative $\delta^{18}O$ and $\delta^{2}H$ indicating that they may be recharged outside of this area.

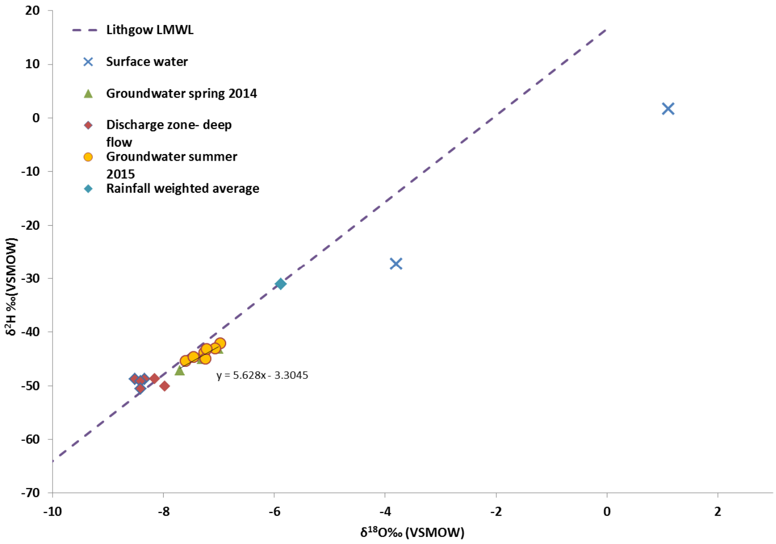

Figure 6 – $\delta^{18}O$ and $\delta^{2}H$ composition for groundwater and surface water

VI. DISCUSSION AND CONCLUSION

The fractured rock system is heavily influenced by structural features (Figures 1 and 7). The most important are the extensional NW trending structures, where the fractures are open and infill comprises quartz. These are considered to be water bearing zones based on the distorted groundwater equipotentials within this zone, and supported by geochemical interpretation. By contrast, NE structures do not act as a water conduit, the fractures are closed and the infill comprises clay. Source of Ca dominated HCO_3 groundwater is the contact with calcite, calcium-magnesium dominated water is a result of contact with dolomite lenses, while Na dominated bicarbonate waters interact with feldspar and plagioclase in volcanics. Na-HCO_3 dominated water is typical for shale, and correlates well with the rock source. Although the chemical composition identifies four geochemical facies, the stable isotope data indicate that the groundwater source is modern precipitation, with a minor shift to the right of LMWL. This reflects evaporation during infiltration through intensely and partially weathered zones.

Temporal groundwater levels and vertical groundwater gradients (over 40 m) indicate that the upper intensely weathered zone is hydraulically separated from deeper partially weathered zone. This is supported by response to rainfall recharge evident in the intensely weathered zone and completely absent in the partially weathered zone. In addition, the response to rainfall in other piezometers is very limited and if it occurs there is a long time lag.

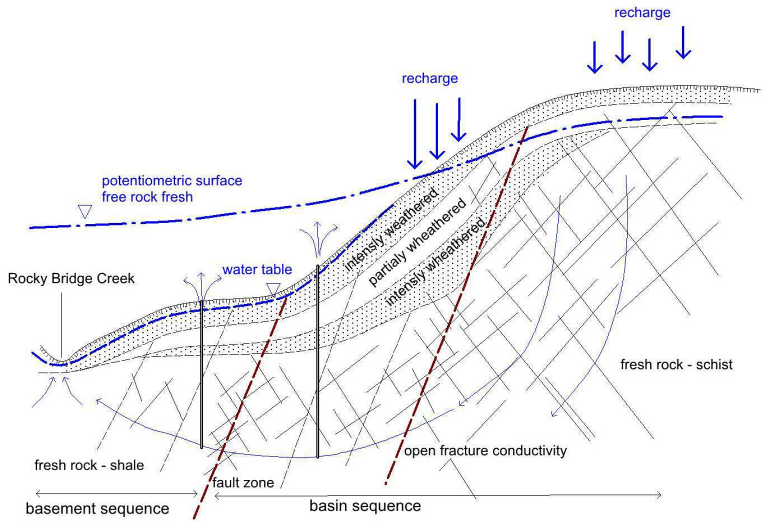

Figure 7 – Conceptual cross sectional groundwater model

The development of distinctive geochemical groups is a reflection of interaction with rocks and dissolution processes. The upward flow from the fractured rock results in mixing of waters with overlaying zones. This mixing is supported by the fact that Mg concentrations are higher where the discharge occurs through the partially and intensely weathered zone as opposed to where discharge occurs where thin weathered units are present.

This paper has demonstrated that continued monitoring and application of combined detailed geology, geochemical and hydrogeological approach improves the conceptualisation and understanding of the connection between the fractured rock and weathered zones.

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