Aquifer interactions and groundwater discharge into streams identified using $^{87}Sr/^{86}Sr$ isotope ratios in the Upper Loddon catchment, central Victoria

S.K. Hagerty and J.A. Webb
Department of Environmental Geoscience
La Trobe University
Melbourne 3086
AUSTRALIA
E-mail: S.Hagerty@latrobe.edu.au

Abstract

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) have been successfully used to trace interactions between the basalt and deep lead aquifers in the upper Loddon valley, central Victoria. Low $^{87}Sr/^{86}Sr$ ratios in deep lead groundwater samples in the south of the catchment show that here the deep lead recharges relatively rapidly through the basalt aquifer. Abnormally high $^{87}Sr/^{86}Sr$ ratios in some basalt groundwater samples further down gradient mark areas where faulting has disrupted deep lead deposition and deep lead groundwater is forced to flow upwards into the basalt aquifer. Strontium isotopes have also been used in conjunction with $\delta^{18}O$ and $\delta^{2}H$ isotope ratios to identify regions of groundwater discharge into streams: saline basement groundwater discharges into the stream at the edge of basement rock outcrop, and basalt groundwater discharges into streams throughout most of the northern half of the catchment.

1. INTRODUCTION

Groundwater supplies in the upper Loddon catchment are under stress due to extraction for irrigation and town supplies. Salinisation of the Tullaroop Reservoir in the upper Loddon is also putting pressure on water resources. Catchment managers require a detailed understanding of the groundwater system, and how this affects surface water salinity, in order to protect supplies into the future.

The $^{87}Sr/^{86}Sr$ isotope ratio of groundwaters, together with the concentration of Sr^{2+}, can be used to identify groundwater flow paths and mixing because groundwater inherits the characteristic strontium isotopic signature of the aquifer it flows through (e.g. Johnson *et al*., 2000; Woods *et al*., 2000). Similarly, strontium isotopes can be used to identify groundwater input into streams (e.g. McNutt, 2000; Negrel, 1999; Shand *et al*., 2007), especially when used in conjunction with other geochemical techniques. Hence, strontium isotopes were used as part of a detailed hydrogeological/ hydrogeochemical study, in order to understand the interactions between aquifers in the upper Loddon and the influence of groundwater discharge on stream composition.

2. METHODS

Groundwater samples were collected from 41 private and public bores in the upper Loddon from 2002 to 2006, after removing at least 3 bore volumes to ensure the samples were uncontaminated. All samples were analysed for the $^{87}Sr/^{86}Sr$ ratio using a Finnigan-MAT 262 Thermal Ion Mass Spectrometer (TIMS) at La Trobe University, Bundoora.

Surface water samples were collected from 10 locations along streams in the upper Loddon in May 2006. Electrical conductivity was measured in the field using a WTW LF330 meter. All samples were analysed for the $^{87}Sr/^{86}Sr$ ratio as described above, and the isotope ratios $\delta^{18}O$ and $\delta^{2}H$ were measured using a Finnigan-MAT 252 Mass Spectrometer at Monash University, Clayton.

3. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The geological basement of the area comprises Ordovician sandstones and shales intruded by Devonian granites. In the early Tertiary a high relief surface was deeply incised into the basement and the valleys (also known as deep leads) infilled by the Calivil Formation. The deep lead sediments fine upwards; coarse sands and gravels are overlain by a finer layer of sands, silts and clays. The deep leads were covered by numerous late Tertiary to Quaternary basalt flows (see Figure 1), disrupting surface drainage. These Newer Volcanics basalts were erupted in two main phases separated by a palaeoregolith (see Figure 2).

The deep lead system was previously thought to be continuous, but a detailed study of the upper Loddon deep lead system (Hagerty *et al*., in review) has revealed that mid-late Tertiary ENE-trending faults disrupted deep lead sediment deposition. This created alternating areas of deep lead thickening and thinning, including regions where deep lead sediments are absent (see Figure 2).

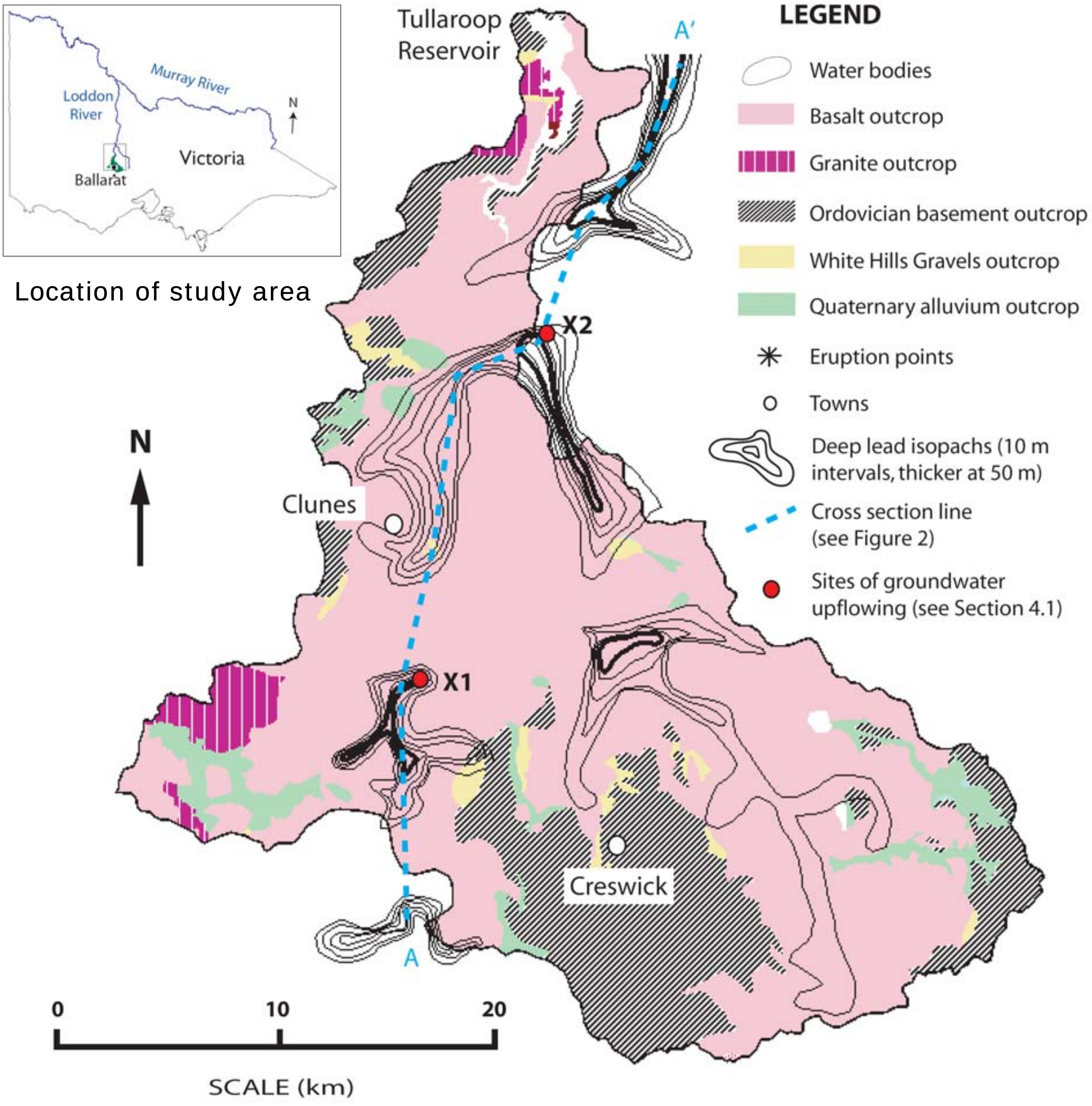

Figure 1 Geology of the upper Loddon area, showing thickness of deep lead sediments. A section line is shown for Figure 2, and points X1 and X2 are sights of upflowing groundwater (see Section 4.1).

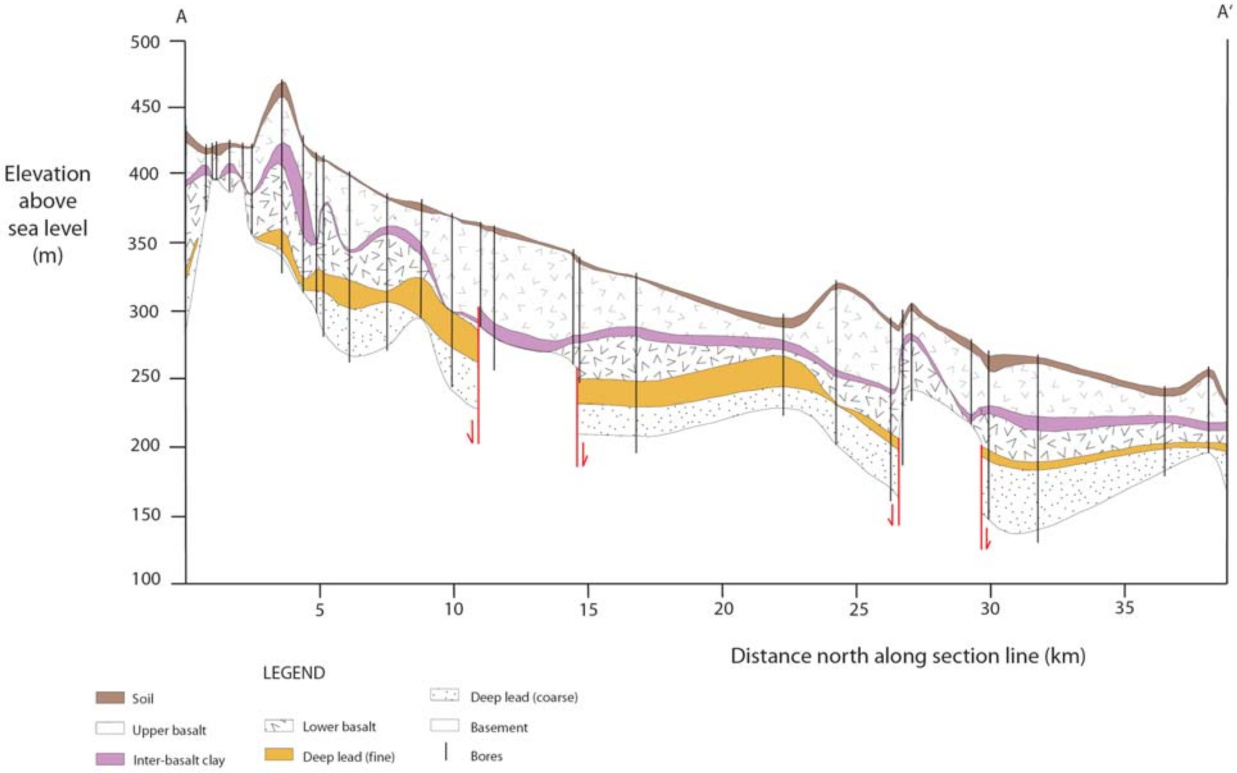

Figure 2 Cross section through the study area (see Figure 1 for location).

The main aquifers in the study area are therefore the Newer Volcanics basalt, deep lead (Calivil Formation) and basement (Ordovician metasediments). Groundwater flows north in all three.

4. RESULTS AND DISCUSION

4.1. Aquifer interactions

Two populations of basalt groundwater exist with respect to their strontium isotope composition; one has a typical basalt groundwater ^{87}Sr/^{86}Sr ratio (group 1; see Figure 3) and the other is more variable and has higher ratios than would be expected for basalt groundwater (group 2; see Figure 3). The high ^{87}Sr/^{86}Sr ratios in group 2 groundwaters cannot be due to differences in basalt composition in the study area; elsewhere in Victoria Price *et al*. (1997) identified a maximum change in the ^{87}Sr/^{86}Sr ratio of 0.002 in different basalt provinces, whereas the maximum difference between basalt groundwater samples in this study is 0.009 (see Figure 3). Furthermore, the bores with elevated ^{87}Sr/^{86}Sr ratios do not all occur in the same region.

Interestingly, the three basalt groundwater samples with the highest Sr ratios occur just upflow of faults where the deep lead thins abruptly (see points X1 and X2 in Figure 2). It is likely that deep lead groundwater, which has a relatively radiogenic isotopic ratio, is forced upwards at these locations, where each fault-bounded section of the aquifer terminates.

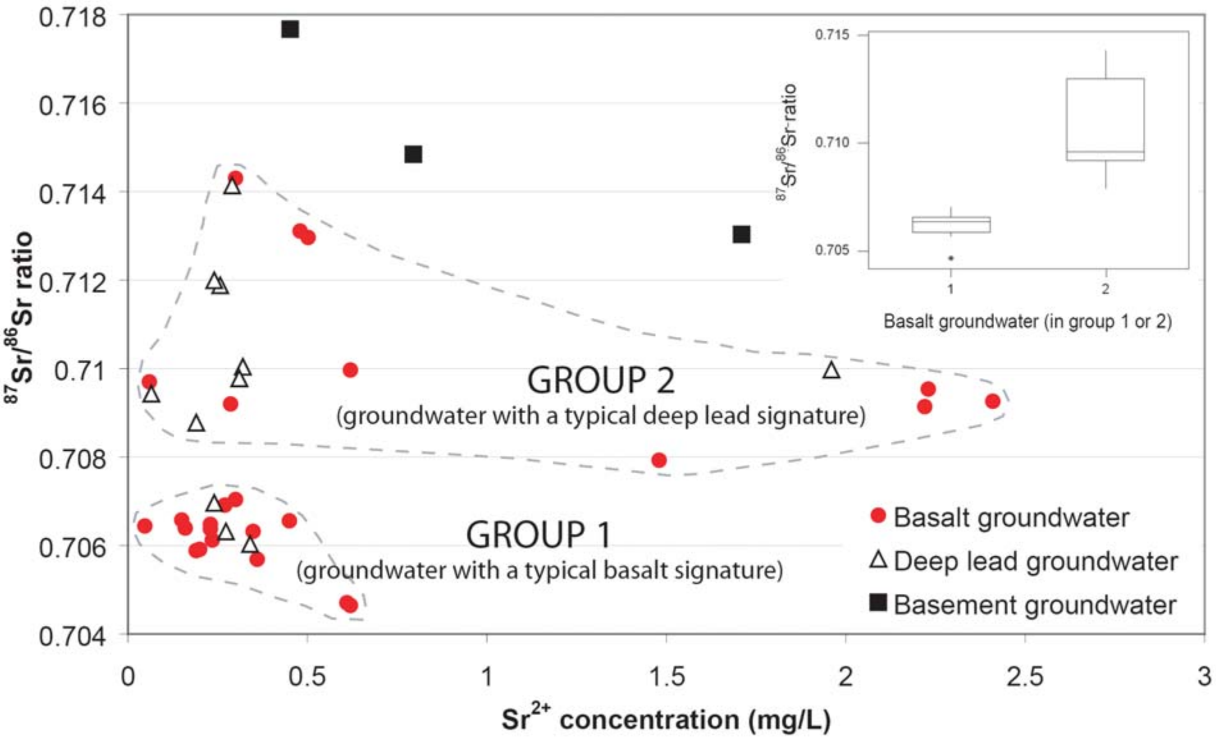

Figure 3 ^{87}Sr/^{86}Sr isotope ratios and Sr^{2+} concentrations of all groundwater samples. A boxplot of ^{87}Sr/^{86}Sr ratio in basalt groundwater samples is inset.

Deep lead groundwater typically has a high strontium ratio similar to that of basement groundwater, since the aquifer is largely composed of weathered basement material. However, three deep lead groundwater samples have lower than expected ratios (see Figure 3); the ratios are more similar to the isotopic signature of the basalt groundwaters. These samples are located in the south of the catchment where there are numerous extinct volcanoes; it is likely that the deep lead is recharged rapidly through the volcanic necks that penetrate the palaeoregolith between basalt flows.

4.2. Groundwater discharge into streams

High seasonal (summer) conductivity of stream flows in the north of the catchment suggests that groundwater discharge dominates stream composition at low flows. This is confirmed by the isotopic composition of these summer stream waters; they have ^{87}Sr/^{86}Sr ratios and Sr^{2+} concentrations intermediate between rainfall (^{87}Sr/^{86}Sr = 0.711100; Sr^{2+} = 0.02 mg/L) and group 1 basalt groundwater (see Figure 4). These samples also show a depleted δ^{18}O/δ^{2}H composition (typical of local groundwater; see Figure 5), or a δ^{18}O/δ^{2}H signature derived from evaporated groundwater (see evaporation trend line in Figure 5).

Surface waters at the northern margin of the Ordovician outcrop, ~7 km north-east of Creswick, have an anomalously high salt concentration. A depleted δ^{18}O/δ^{2}H signature (see red circle in Figure 5) confirms that this is a result of saline groundwater discharge, and the strontium isotope signature suggests that Ordovician basement groundwater is the source (^{87}Sr/^{86}Sr = 0.711994; see Figure 4).

Streams in the south-east of the catchment are not significantly influenced by groundwater discharge; the δ^{18}O/δ^{2}H compositions lie on the local meteoric water line (i.e. they have a rainfall signature; see Figure 5), and the strontium isotope composition closely reflects that of rainfall (see Figure 4).

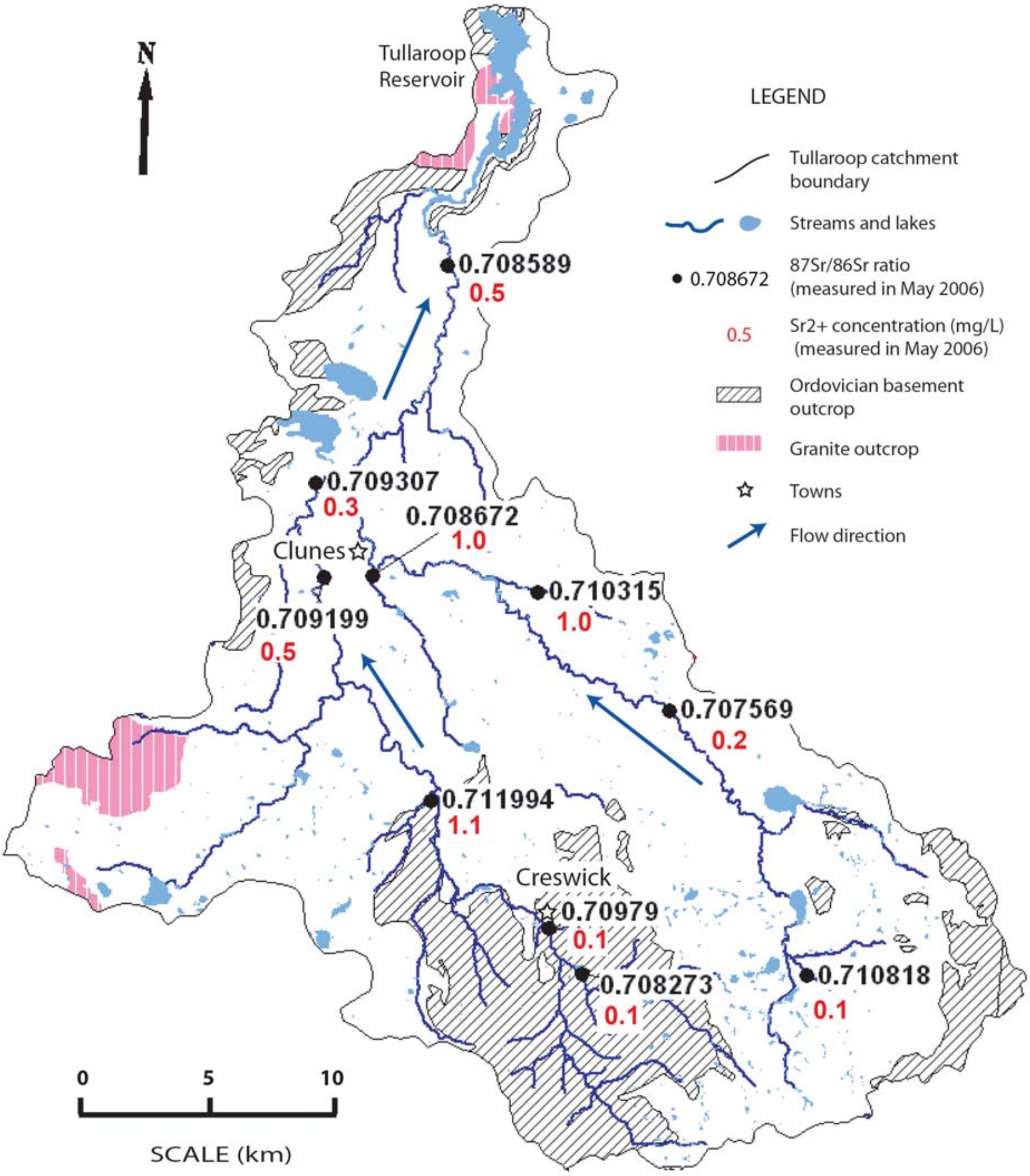

Figure 4 The $^{87}Sr/^{86}Sr$ isotope ratios and Sr^{2+} concentrations of all surface water samples.

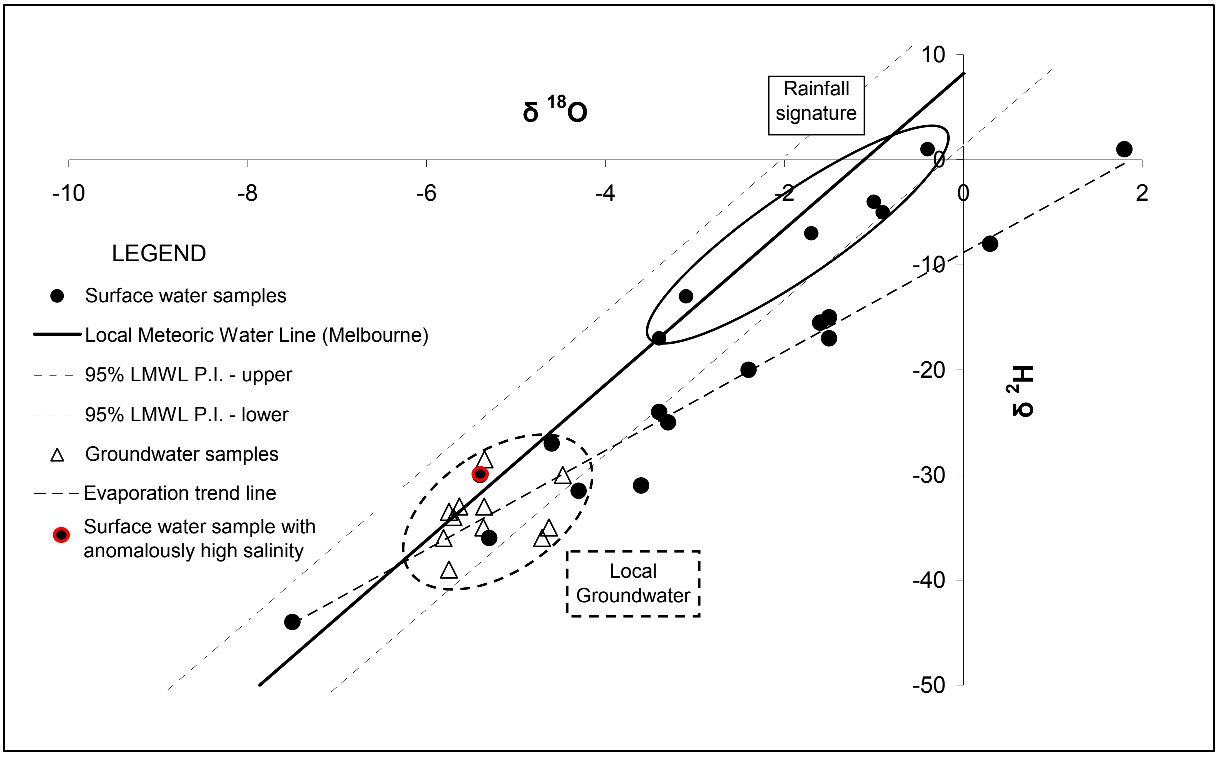

Figure 5 δ^{2}H versus δ^{18}O in surface water and groundwater samples, with the Local Meteoric Water Line (LMWL) at Melbourne and it's 95% Prediction Interval (P.I.), and the evaporation trend line in the surface water data.

5. CONCLUSIONS

Abnormally high ^{87}Sr/^{86}Sr ratios in some basalt groundwater samples confirm that deep lead groundwater is forced to discharge into the basalt aquifer where faulting has disrupted sediment deposition. Low ^{87}Sr/^{86}Sr ratios in deep lead groundwater in the south of the catchment indicate that here the deep lead is recharged relatively rapidly through the basalt aquifer.

Strontium ratios intermediate between rainfall and basalt groundwater, as well as depleted δ^{18}O and δ^{2}H isotope ratios, show that groundwater dominates stream composition in the northern half of the catchment. In particular, highly saline basement groundwater discharges into the stream at the edge of the basement outcrop.

6. ACKNOWLEDGMENTS

This work was supported by funding from Primary Industries Research Victoria (PIRVic), and was conducted in collaboration with Dr Jon Fawcett at PIRVic.

7. REFERENCES

Hagerty, S.K., Fawcett, J. and Webb, J.A. (in review), *The Upper Loddon 'deep lead' palaeodrainage systems are discontinuous due to Mid Tertiary ENE-trending faults*. Australian Journal of Earth Sciences

Johnson, T.M., Roback, R.C., McLing, T.L., Bullen, T.D., DePaolo, D.J., Doughty, C., Hunt, R.J., Smith,R.W., Cecil, L.D. and Murrell, M.T. (2000), *Groundwater fast paths in the Snake River Plain* *aquifer: Radiogenic isotope ratios as natural groundwater tracers*, Geology, 28, 871- 874.

McNutt, R.H. (2000), *Strontium Isotopes*., in Cook, P. and Herczeg, A.L. (eds), “Environmental Tracers in Subsurface Hydrology”, Kluwer Academic Publishers, USA, pp. 233-260.

Negrel, P. (1999*) Geochemical Study of a Granitic Area: The Margeride Mountains, France: Chemical Element Behavour and $^{87}Sr/^{86}Sr$ Constraints, Aquatic Geochemistry*, 5, 125 – 165.

Price, R.C., Gray, C.M. and Frey, F.A. (1997), *Stronitum isotopic and trace element heterogeneity in the plains basalts of the Newer Volcanics Province, Victoria, Australia*, Geochimica et Cosmochimica Acta, 61, 171- 192.

Shand, P., Darbyshire, F.D.P., Gooddy, D., Haria, A.H. (2007) *$^{87}Sr/^{86}Sr$ as an indicator of flow paths and weathering rates in the Plynlimon experimental catchments, Wales, U.K.* Chemical Geology, 236, 247 - 265.

Woods, T.L., Fullagar, P.D., Spruill, R.K. and Sutton, L.C. (2000), *Strontium Isotopes and Major Elements As Tracers of Ground Water Evolution: Example from the Upper Castle Hayne Aquifer of North Carolina*, Ground Water, 38, 762- 771.