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Strontium isotopes as tracers to delineate aquifer interactions and the influence of rainfall in the basalt plains of southeastern Australia

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SUMMARY

To better understand the spatial distribution of groundwater salinisation in western Victoria, southeast Australia, the interactions between a surficial basalt aquifer and an underlying extensive palaeodrainage (‘deep lead’) system were studied using a multi-disciplinary approach, combining strontium isotope analyses with major ion chemistry and the interpretation of geological and hydrogeological data. The strontium isotopes proved particularly useful in delineating flow paths and hydraulic connections between the two aquifers, which have contrasting $^{87}Sr/^{86}Sr$ ratios. The freshest basalt groundwaters lie beneath volcanoes and have $^{87}Sr/^{86}Sr$ signatures close to the whole-rock strontium isotope ratios of the basalts ($\sim$0.7045), indicating the strong influence of basalt weathering. With increasing distance from the eruption points, basalt groundwaters become progressively more saline and the strontium isotope ratios evolve towards the more radiogenic signatures of local rainfall (0.710–0.711), due to the slow addition of infiltration concentrated by evapotranspiration during its passage through the thick, clay-rich soils developed on the basalt lavas. Overall, the influence of rainwater on the strontium isotope signatures of the basalt groundwater is much greater than that of basaltic weathering, indicating that rainwater can play a greater role in determining groundwater strontium composition than is often realised. Most parts of the palaeodrainage system beneath the basalt are preferentially recharged through the volcanoes, as shown by strong downwards hydraulic gradients and groundwater $^{87}Sr/^{86}Sr$ ratios similar to the least radiogenic basalt groundwaters. However, in the northwestern part, groundwater $^{87}Sr/^{86}Sr$ ratios are closer to those of the source material of the sediments (Palaeozoic bedrock), indicating that here recharge occurs predominantly in the headwaters where the basalts are absent. In the southern and western sections of the palaeodrainage system there is an upward flux into the overlying basalts, as shown by strong upward hydraulic gradients and elevated strontium isotope signatures in basalt groundwaters. This occurs because lateral groundwater flow in the palaeodrainage system is restricted by shallow subsurface basement ridges, and ultimately discharges to the surface as salt lakes.

Introduction

The sustainable management of catchment-scale groundwater resources in complex multi-aquifer systems requires a detailed understanding of the recharge mechanisms and hydraulic interactions between the aquifers, in order to avoid overexploitation or cross-aquifer contamination. In such settings, isotopes are often cost-effective and powerful natural tracers. One of the isotopic tracers most commonly applied is the $^{87}Sr/^{86}Sr$ ratio, which is controlled by water–rock interaction and water-mass mixing (McNutt, 2000). Decay of ^{87}Rb forms ^{87}Sr, but the long half-life (4.967×10^{10} years; Kossert, 2003) means that this process does not significantly affect the $^{87}Sr/^{86}Sr$ ratio except on very long time scales (Faure, 1991; McNutt, 2000).

In previous studies throughout the world, strontium isotopes have been used to characterize groundwater flowpaths in often complex hydrogeological settings (e.g. Johnson and DePaolo, 1994; Harrington and Herczeg, 2003; Gosselin et al., 2004; Klaus et al., 2007; Shand et al., 2007; Uliana et al., 2007; Cartwright et al., 2007), identify mixing of water of different sources (e.g. Woods et al., 2000; Frost and Toner, 2004; Singleton et al., 2006) or investigate mineral weathering reactions (e.g. Dasch, 1969; Brass, 1975; Åberg et al., 1989; Bullen et al., 1996; Clow and Drever, 1996; Bullen and Kendall, 1998).

In western Victoria, southeastern Australia, groundwater quality is often poor and groundwater salinisation is a serious issue, reducing agricultural productivity. Prolonged drought conditions over the last 10 years have increased the demand for good quality groundwater, and the projected reduction in rainfall and increase

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in evaporation due to climate change (e.g. Suppiah et al., 2007) will put groundwater systems in this area under greater stress. For the sustainable management of the limited groundwater resources in western Victoria, a detailed knowledge of the complex interactions between the aquifer systems is required, to supplement the broad-scale studies carried out to date (Nolan et al., 1990; Mann et al., 1992). In the present study, strontium isotope groundwater and rainwater signatures have been combined with major ion chemistry and geological and hydrogeological data to construct a conceptual groundwater model which describes recharge- and salinisation mechanisms and the hydraulic connections between the two main aquifers in the area: basalts and underlying Tertiary siliciclastic sediments derived from weathering of granites and metamorphic rocks. The contrasting lithologies and distinct $^{87}Sr/^{86}Sr$ ratios of the aquifers and rainfall make strontium an ideal tracer to identify groundwater flow paths and aquifer interactions, as well as to study the influence of rainwater on the $^{87}Sr/^{86}Sr$ ratios of groundwater.

Regional setting

The study area forms the eastern catchment of the Hopkins River, located ~200 km west of Melbourne in southeastern Australia (Fig. 1). It has a temperate climate with hot summers and mild winters. Evaporation exceeds precipitation except from June to September. Annual rainfall increases from about 550 mm in the central part of the study area to over 700 mm in the north due to orographic rainfall along the Western Uplands.

Much of western Victoria is occupied by the extensive, gently undulating plain of the Newer Volcanic Province, composed of basalts erupted during three distinct phases (Bennetts et al., 2003): 4–6 Ma (phase 1), ~2–3 Ma (phase 2) and 0.3 Ma to ~8000 years ago (phase 3). Eruption points are well preserved and the volcanic cones form prominent landscape features, and along with the youngest 3rd phase basalt flows, have thin soils and rocky outcrops. The youngest basalts are primarily alkali olivine basalts, whereas the older phase one and two basalts, which are generally covered by thick, clay-rich soils up to 10 m thick, are dominantly tholeiitic and transitional (Price et al., 1997). Basalt thicknesses range between 30 and 130 m, and the basalts form the major unconfined to semi-confined regional aquifer system in the study area.

Beneath the basalts is an extensive buried palaeovalley (the Streatham Deep Lead System; Holdgate et al., 2006; Raiber and Webb, 2008), which covers more than 2500 km^2 (Fig. 1) and is one of the largest palaeovalley (deep lead) systems in southeastern Australia. It is incised into Palaeozoic basement, which consists of granites, granodiorites, sediments and meta-sediments. The deep lead system is composed of five major south-flowing tributaries, which fuse into a central depression consisting of several grabens

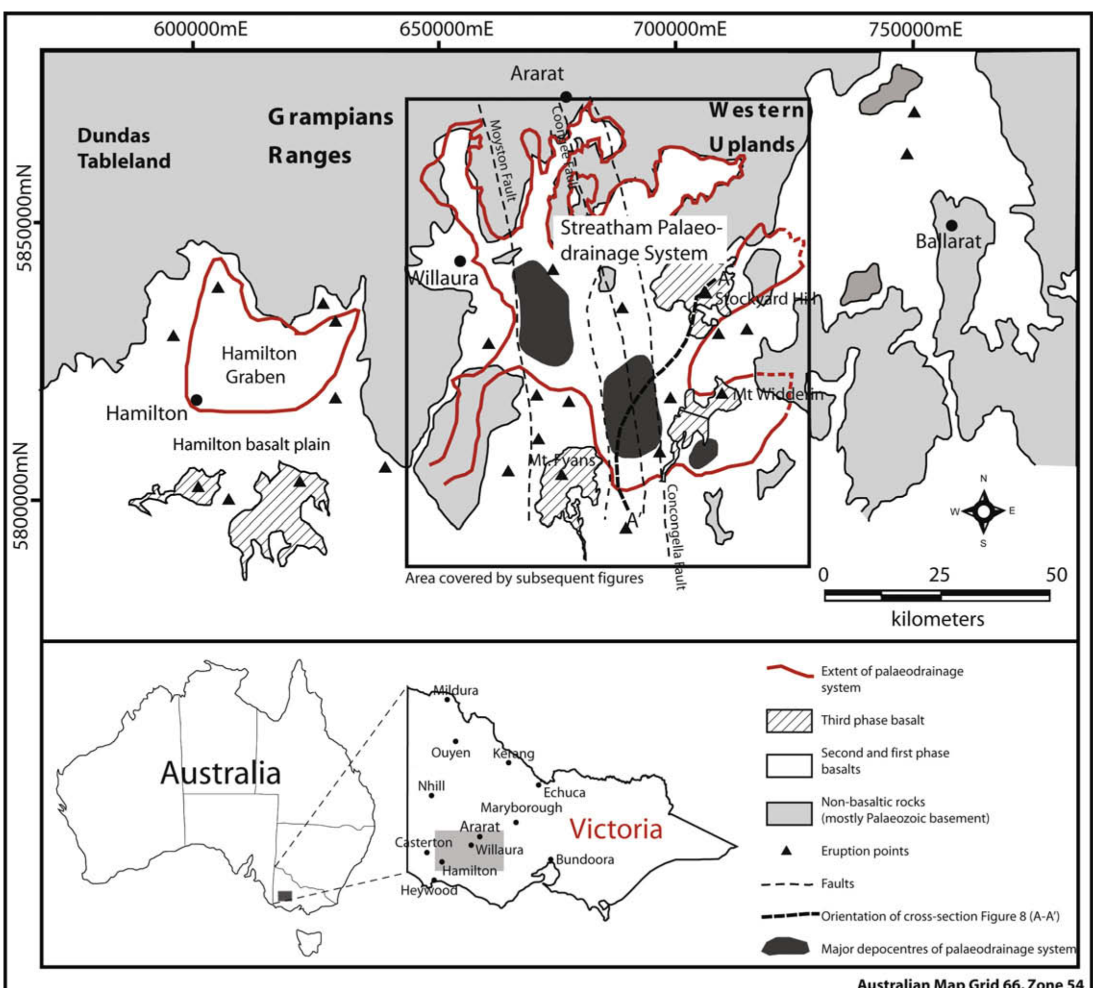

Fig. 1. Regional setting of study area including the Streatham Deep Lead System, the location of the major depocentres and their bounding faults (from Raiber and Webb, 2008), and locations of section line in Fig. 9(B–B′).