The Thermal Springs of the Table Mountain Group: A Stable Isotope Study

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Abstract

Thermal springs ranging in temperature up to 64°C issue from rocks of the Table Mountain Group (TMG) which indicate deep (in some cases > 2 km) circulation of groundwater. The δD and $\delta^{18}O$ values of the springs range from -46 to -18‰ and -7.3 to -3.9‰ respectively. Although the thermal springs have isotope compositions that plot close to the local meteoric water line, their δD and $\delta^{18}O$ values are significantly lower than ambient meteoric water, or groundwater. It is therefore suggested that recharge of most springs is at significantly higher altitude than the spring. The isotope ratios decrease with increasing distance from the west coast, which is in part related to the continental effect. However, a negative correlation between spring water temperature and $\delta^{18}O$ value in the springs closest to the west coast indicates a progressive increase in the average altitude of recharge away from the coast.

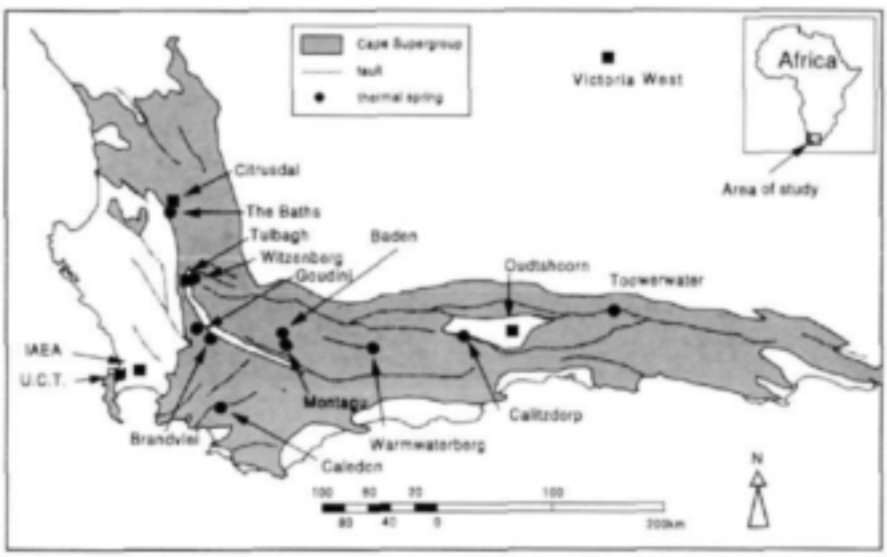

Figure 1

Sketch map of the Western cape showing the location of thermal springs sampled. The location of rainfall monitoring stations at the University of Cape Town (UCT), Cape Town International Airport (IAEA), Citrusdal, Tulbagh and Oudtshoorn are also shown. The thermal spring at Citrusdal is known as "The Baths" but to avoid confusion it is referred to as Citrusdal in the text. The area of outcrop of the Cape Supergroup forming the Cape Fold Belt mountains is indicated (taken from Theron et al., 1991).

Introduction

There are over eighty seven thermal springs in South Africa ranging in temperature from 25-64°C. They are not associated with recent volcanic activity, which is unknown in this part of Africa. The geology and chemical composition of the springs have been described by Kent (1949), Hoffmann (1979) and Meyer (2001). Most Western Cape thermal springs issue from rocks of the TMG where faulted and highly jointed quartzites and sandstones of the Cape Fold Belt act as the main deep aquifer. In this case study, we review hydrogen, oxygen, tritium and ^{14}C isotope data, and some trace element data for TMG thermal springs from existing publications by Mazor and Verhagen (1983), Diamond (1997) and Diamond and Harris (2000). The aim is to show how isotope data have been used to constrain the nature of the recharge and mechanism(s) of heating of the thermal springs.

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Spring	Temp (°C)	Flow (ℓ/s)	Alt. (m)	Dist. (km)	Geological environment
Baden	37	38	280	150	TMG-Bokkeveld Group contact, near regional fault
Brandvlei	64	126	220	90	TMG-Bokkeveld Group contact, regional fault
Caledon	50	9	360	100	TMG-Bokkeveld Group contact, near regional fault
Calitzdorp	52	27	200	310	TMG-Bokkeveld Group contact, near regional fault
Citrusdal	43	29	250	80	Fault in Nardouw Subgroup of TMG
Goudini	40	11	290	80	Regional fault in TMG
Montagu	43	38	280	155	TMG-Bokkeveld Group contact, near regional fault
Towerwater	44	11	800	455	Regional fault in TMG
Warmwaterberg	45	9	500	225	Near top of Nardouw Subgroup, near regional fault
Witzenberg	~28	~1	800	105	Peninsula Formation

Table 1
General information about thermal springs sampled

Distance = distance from the West Coast measured in a straight line with an E-W orientation.
Modified from Diamond (1997).

All groundwater that sinks to any appreciable depth will become heated because of the geothermal gradient. Mazor (1991) suggested a purely arbitrary temperature divide between cold springs and thermal springs of 6°C above average annual surface temperature. The Western Cape valleys and coastal plains experience annual average temperatures between 15°C and 20°C, so any water discharging at or above about 26°C can be classified as a thermal spring. In the Western Cape, there is a full gradation from cold (<20°C) to the hottest spring in the country, Brandvlei, 64°C. Data from all of the well known thermal springs in the area were sampled during this work (Table 1). The majority are above 40°C, with one spring, Witzenberg (28°C) just falling within the classification of thermal. Most of the springs are found at relatively low altitude (<300 m), with two springs found at 700 m or above (Towerwater and Witzenberg). The spring with the highest yield (Brandvlei) is also the hottest, whereas most of the springs with low discharge are relatively cool. This may in part be due to more effective cooling by heat loss to the surrounding rock in the case of the springs with low yield. Diamond (1997) and Diamond and Harris (2000) suggested on the basis of the likely geothermal gradient that the thermal water at Brandvlei must come from an average depth of 2.35 km. This estimate is in agreement with geological cross sections (Diamond and Harris, 2000).

Results

Chemistry

Chemical data for three TMG springs (Goudini, Brandvlei and Calitzdorp) were presented by Mazor and Verhagen (1983). Compared to hot springs located in other source rocks in South Africa, these springs have low total dissolved ions (< 200 mg/ℓ) with no group of ions dominating.

Carbon isotope data and tritium

Mazor and Verhagen (1983) obtained a range of $\delta^{13}C$ values from -18.9 to -24.5‰ for dissolved bicarbonate in some Western Cape springs (Montagu, Caledon, Brandvlei, Goudini and Citrusdal). Diamond (1997) measured the $\delta^{13}C$ values of CO_2 gas discharged with the spring water at Brandvlei and Calitzdorp and obtained $\delta^{13}C$ values of -22.7 and -21.5‰ respectively. Mazor and Verhagen (1983) determined the ^{14}C content of five of the springs (Table 2) which vary from 47 to 78 pmC (per cent modern carbon). These authors also measured the tritium content of five of the springs and found that only Citrusdal and Goudini have tritium slightly above 1 TU (tritium unit; 1 TU = $^3H/^1H$ of 10^{-18}). Because of the possibility of contamination at the time of sampling (Mazor and Verhagen, 1983), values below 1 TU can be regarded as tritium-free.

Hydrogen and oxygen isotopes

Water δD and $\delta^{18}O$ values are presented in Table 1 and are plotted against altitude and temperature in Fig. 2. The $\delta^{18}O$ vs. temperature plot shows two distinct groups of samples with negative correlation. The springs plotting in the upper group are Goudini, Caledon, Citrusdal and Brandvlei all of which are found in the belt of mountains closest to the coast (the "coastal group"). The springs which plot on the lower group are found in the mountain belts further inland (Fig. 1). This negative correlation is less strong for δD vs. temperature. There is no correlation between isotope ratios and height above sea level. For those springs less than 200 km from the west coast (Fig. 3), there is a good correlation between isotope ratios and distance from the west coast.

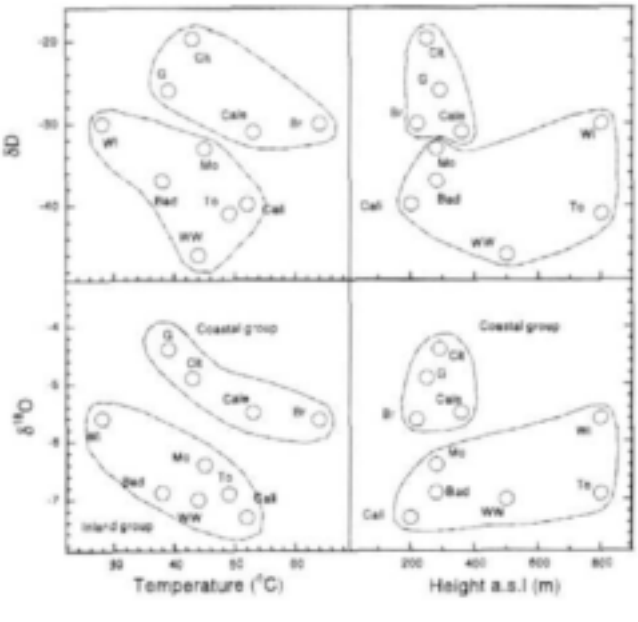

Figure 2

Plot of δD and δ18O values of thermal springs vs. temperature and height of spring above sea level. Cit = Citrusdal, G = Goudini, Cale = Caledon, Br = Brandvlei, Wi = Witzenberg, Bad = Baden, WW = Warmwaterberg, To = Toowerwater, Cali = Calitzdorp.

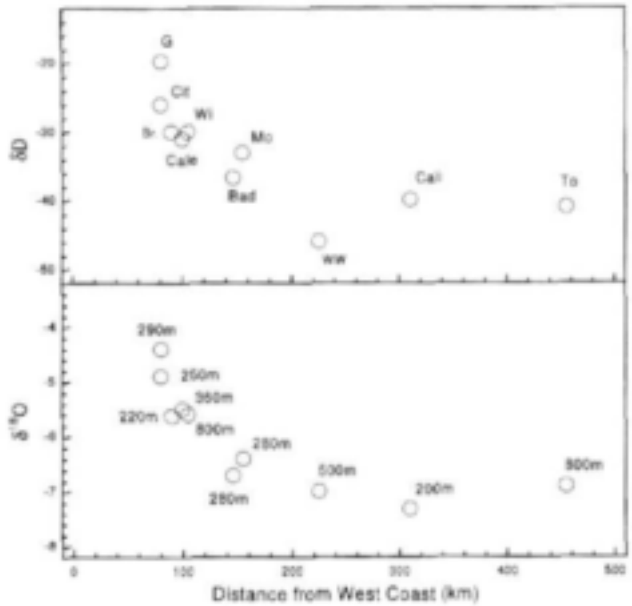

Figure 3

Plot of δD and δ18O of thermal spring water vs. distance from the west coast of southern Africa measured in an E-W direction. Abbreviations for springs in upper diagram as for Fig. 2. In lower diagram, height above sealevel for each spring is indicated.

Table 2
Isotope data for thermal springs

Spring	TDI (mg/ℓ)	δD	$\delta^{18}O$	$\delta^{13}C$ gas	$\delta^{13}C$ HCO_3^-	TU	^{14}C (pmC)
Baden		-37	-6.9				
Brandvlei	100	-30	-5.6	-22.7	-18.9	0.5±0.3	70.7
Caledon		-31	-5.5		-21.6	0.8±0.3	47.2
Calitzdorp	170	-40	-7.3	-21.5		0.3±0.3	
Citrusdal		-20	-4.9		-20.0	1.1±0.3	70.7
Goudini	91	-26	-4.4		-24.5	1.1±0.3	78.2
Montagu		-33	-6.4		-21.3		49.1
Toowerwater		-41	-6.9				
Warmwaterberg		-46	-7.0				
Witzenberg		-30	-5.6				

Notes: TDI = total dissolved ions, TU = tritium units, pmC = percent modern carbon. TDI, bicarbonate $\delta^{13}C$, tritium and ^{14}C data from Mazor and Verhagen (1983) on samples collected in 1971-2. Oxygen, hydrogen and gas $\delta^{13}C$ data from Diamond and Harris (2000). H, O and C isotope data are reported in the familiar δ notation, relative to SMOW, where $\delta = (R_{sample}/R_{SMOW} - 1)*1000$, and R = $^{18}O/^{16}O$, D/H or $^{13}C/^{12}C$.

Discussion

Carbon isotopes and tritium

The gas and the dissolved bicarbonate $\delta^{13}C$ values (-18.9 to -24.5‰) clearly label the carbon as being of organic rather than volcanic origin. The $\delta^{13}C$ values of the gas samples of -21.5 and -22.7‰ are much lower than the typical $\delta^{13}C$ values for volcanic and geothermal CO_2 of 0 to -11‰ (Taylor, 1986). The most likely source for the carbon is soil and vegetation at the area of recharge (Diamond, 1997; Diamond and Harris, 2000).

The low tritium content indicates that the water in all the springs (except perhaps Citrusdal and Goudini) contains little or no recent (post 1952) water. The ^{14}C data are harder to interpret because the initial ^{14}C content at recharge is not known. Mazor

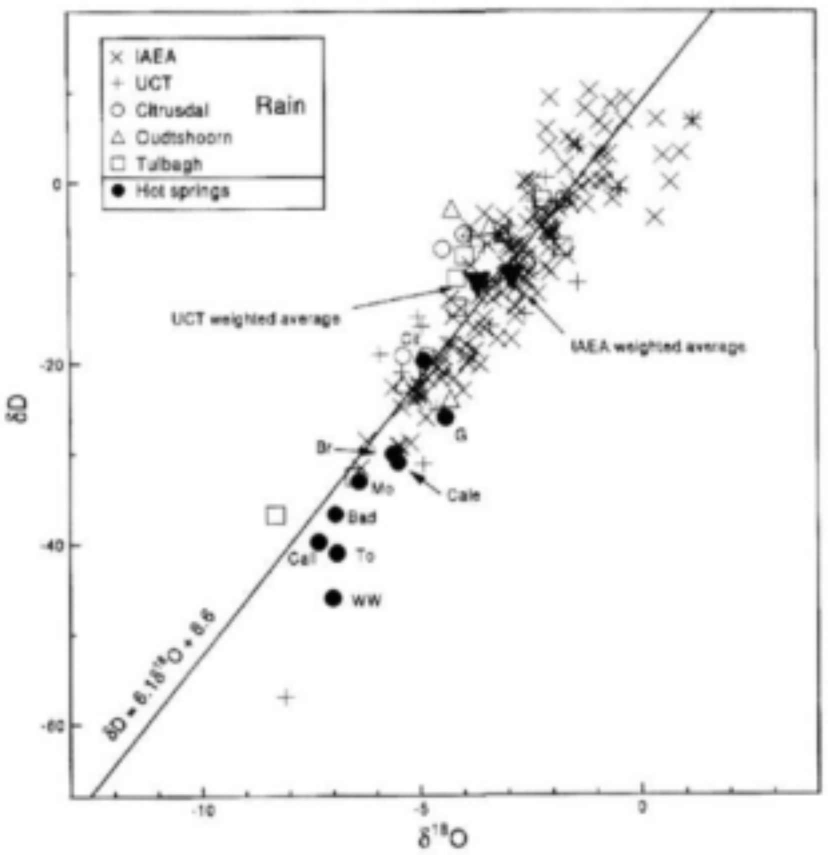

Figure 4

Plot of δD vs. δ18O for thermal springs and rain water from various places. All rain data are integrated monthly samples; the UCT data are for a two-year period (Diamond and Harris, 1997) and the IAEA data for most (but not all) months between 1962 and 1974 (IAEA, 1997); the Citrusdal, Oudtshoorn and Tulbagh data are for March-October 1995. The weighted annual mean values for the UCT and IAEA collection stations are shown and the line of best fit through the rain data is from Diamond and Harris (1997).

and Verhagen (1983) suggest, on the basis of low $\delta^{13}C$ values, that the initial ^{14}C contents were high and that no exchange with ^{14}C carbonate material took place. Brandvlei, Citrusdal and Goudini have 71-78 pmC which Mazor and Verhagen interpret to represent short turnover times. Montagu and Caledon have lower ^{14}C content (49 and 47 pmC respectively) which led Mazor and Verhagen to suggest turnover times of several thousand years.

Comparison with meteoric water

One of the main conclusions of both Mazor and Verhagen (1983) and Diamond (1997) was that the thermal springs have systematically lower δD and $\delta^{18}O$ values than expected for ambient meteoric water. The ideal comparison would be with rainwater collected at the spring site over a period of several years, but such data are not available. The International Atomic Energy Agency database (IAEA, 1997) has a monthly rainfall isotope record for Cape Town International Airport from 1962-1974, and a five year record (1995-2000) exists for the University of Cape Town (Harris, unpublished data). The rainfall data are compared to the thermal spring data on Fig. 4 and it can be seen that the springs have systematically lower δD and $\delta^{18}O$ values compared to the rain, and the weighted mean annual δD and $\delta^{18}O$ values for UCT and the IAEA data. Also plotted on Fig. 4 are rain data from inland stations at Oudtshoorn, Citrusdal and Tulbagh (Diamond and Harris, 1997). These are not complete annual records, nevertheless they all include the winter months when rainfall is highest, temperature lowest.

The average spring δD and $\delta^{18}O$ values for Citrusdal are -20 and -4.9‰ compared to the weighted mean for rain at Citrusdal (Diamond, 1997) of -11 and -4.4‰. The average spring δD and $\delta^{18}O$ values for Witzenberg are -30 and -5.5‰ compared to the weighted mean for rain (Diamond, 1997) for Tulbagh of -20 and -5.1‰. These data are consistent with the Citrusdal and Witzenberg springs being recharged by ambient rain water. The Calitzdorp spring has the lowest δD and $\delta^{18}O$ values of all the springs analysed and these values (δD and $\delta^{18}O$ = -40 and -7.3‰, respectively) are considerably lower than rainfall at Oudtshoorn 40 km east of Calitzdorp Spa, at the same altitude (weighted mean δD and $\delta^{18}O$ = -11.6 and -4.1‰, respectively). No data for rainfall in the vicinity of Montagu, Baden, Warmwaterberg, Towerwater and Rietfontein exist, but there is no reason to suppose that it should be significantly different from the analysed rainfall samples. It is therefore concluded that some of the thermal springs have isotope ratios that are significantly lower than ambient rainfall.

Comparison with groundwater

We have chosen to compare the thermal spring data with data (Harris et al., 1999) from cold springs issuing from the lower slopes of Table Mountain (next to UCT in Fig. 1), and water sampled from boreholes in the area around Victoria West (altitude 1 200 m; Fig. 1) in the SW Karoo (C. Harris, unpublished data). These data give some idea of the range of δD and $\delta^{18}O$ values of unheated ground water compared to the thermal springs. The Victoria West water samples were taken from various depths (0-250 m) from a number of boreholes drilled by the Department of Water Affairs and Forestry in the area. The Table

Mountain springs plot close to the local meteoric water line (Diamond and Harris, 1997) whereas the Victoria West borehole waters form an array through which the line of best fit has the equation $\delta D = 6.9 * \delta^{18}O - 1.8$. The negative intercept value is uncharacteristic and may reflect significant evaporation in the near surface environment during recharge. The thermal springs plot between the lines of best fit through the Table Mountain and Victoria West data. They have significantly lower δD and $\delta^{18}O$ values than and generally have lower $\delta^{18}O$ values.

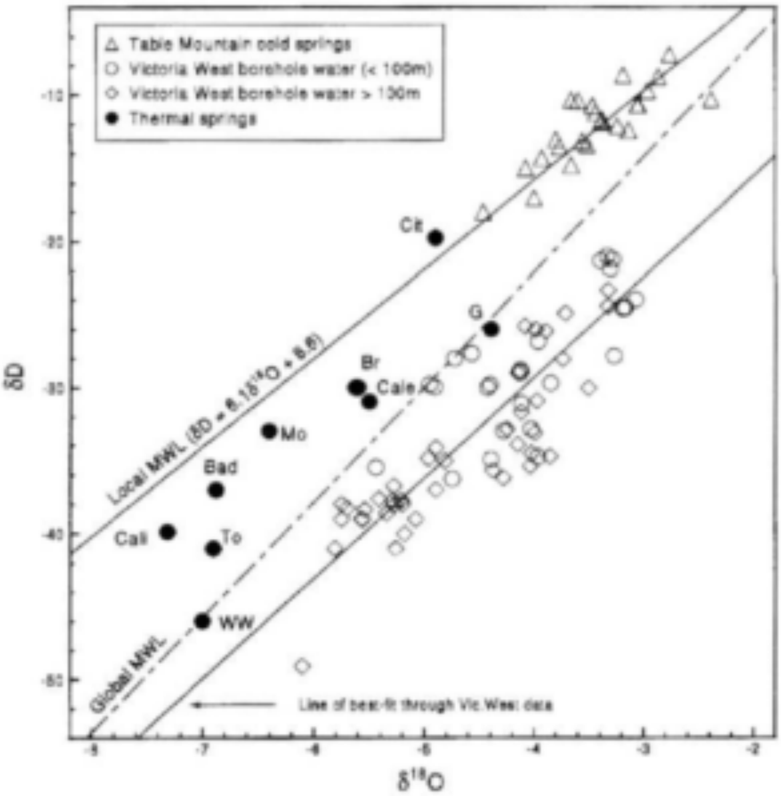

Figure 5

Comparison of thermal spring δD and $\delta^{18}O$ values with those of cold springs on the lower slopes of Table Mountain (Harris et al., 1999) and water sampled from various levels from deep boreholes in the area around Victoria West (Harris, unpublished data). Water collected from < 100 m depth and from > 100 m depth are distinguished. The local meteoric water line (MWL) for the Western Cape is from Diamond and Harris (1997). The line of best-fit through the Victoria West data was calculated using the reduced major axis method. The Global Meteoric Water Line of Craig (1961) is shown for reference.

Origin of low δD and $\delta^{18}O$ values

The comparison of δD and $\delta^{18}O$ values between the thermal springs and meteoric and groundwater data indicates that the thermal springs have significantly lower δD and $\delta^{18}O$ values than expected for ambient rain. Various combinations of the following may be responsible for these low δD and $\delta^{18}O$ values:

- The continental effect (e.g. Dansgaard, 1964)
- Selective recharge during periods of abnormally high rainfall (as suggested by Mazor and Verhagen, 1983)
- Recharge during a earlier period of colder climate
- Recharge at altitudes significantly higher than the springs.

Figure 5 suggests that the continental effect, alone, cannot account for the low δD and $\delta^{18}O$ values of the thermal springs. Selective recharge during heavy rains is unlikely to explain the difference in isotope composition between the cold groundwaters and the thermal springs. The possibility that the springs were recharged during a colder climate regime was rejected by Mazor and Verhagen (1983) because of the lack of correlation between ^{14}C data (as a proxy for time) and oxygen and hydrogen isotope ratios.

There remains the possibility that high average altitude of recharge is the cause of the low isotope ratios of the thermal springs. It is well known that the δD and $\delta^{18}O$ values of rainfall decrease as altitude increases (Dansgaard, 1964). Midgley and Scott, (1994) reported an altitude effect on $\delta^{18}O$ of -0.32‰ per 100 m for the Jonkershoek Mountains, about 70 km east of Cape Town. At Calitzdorp, the possibility exists that the zone of recharge of the spring could be in the Klein Swartberg mountains to the north, which rise up to 2 000 m (Fig. 2). The difference between the $\delta^{18}O$ value of the spring and Oudtshoorn rain is 3.2‰ which could be interpreted as the recharge zone being on average 1 000 m higher than the spring that is at about 1 200 m. Geological cross-sections presented by Diamond (1997) and Diamond and Harris (2000) show that this interpretation is hydrologically reasonable.

Regional variation

The small number of thermal springs precludes a detailed discussion on the regional variation of their δD and $\delta^{18}O$ values. Nevertheless the stable isotope data present several interesting features. The most obvious feature is the apparent effect of continentality whereby the δD and $\delta^{18}O$ values decrease with increasing distance from the west coast. The difference between the Table Mountain springs data and the Victoria West groundwater data illustrate a second effect, that is a much lower "deuterium excess" d, where $d = \delta D - 8 * \delta^{18}O$ for a given data point (Dansgaard, 1964; Whelan, 1987), for the inland groundwater. Regardless of whether the low y-axis intercept value for the line of best fit through the Victoria West data is indicative of evaporation prior to recharge, the thermal springs also show a similar decrease in deuterium excess as their distance from the west coast increases.

The apparent grouping of thermal springs into coastal and inland groups (Fig. 3) which both show a negative correlation between $\delta^{18}O$ and water temperature is more difficult to explain in the light of the observations made above. Within each group, higher temperatures of spring water can only be explained by circulation of water to greater depths. As discussed above, lower δD and $\delta^{18}O$ values can generally be explained by recharge at higher altitude, thus the data are consistent with the higher temperature springs being recharged at higher altitude. This is to be expected as a greater depth of circulation would be expected in aquifers with greater hydraulic head. The correlation between $\delta^{18}O$ value and distance from the west coast in the coastal group must, therefore, reflect an increase in the average altitude of recharge with increasing distance from the coast and is not simply due to the continental effect. The inland group of thermal springs shows a negative correlation between $\delta^{18}O$ value and water temperature with a similar gradient, but with $\delta^{18}O$ values about 2‰ lower for a given temperature. This offset is presumably due to the greater continentality of these springs. The lack of correlation between distance from the west coast and isotope ratios in those springs > 200 km from the west coast (Fig. 3) may in part be due to the change in geometry of the Cape Fold belt from east to west. The coastal group of thermal springs is located in mountain belts which trend N-S, perpendicular to the movement of weather systems, whereas the inland group is situated in mountain belts which trend E-W.

Conclusions

The source of water in the Western Cape thermal springs is meteoric in origin, and the high temperature of some of the springs can only be explained by deep circulation. Low tritium contents show that the water is pre 1952 in age, and ^{14}C data suggest variable turnover times of up to a few thousand years. The thermal springs differ from ambient meteoric water in their significantly lower δD and $\delta^{18}O$ values. Although the isotope ratios of the thermal springs become progressively more negative with increasing distance from the west coast (for the first 200 km), it appears that high average recharge altitude is the most important factor responsible for the low δD and $\delta^{18}O$ values.

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