Annual shifts in O- and H-isotope composition as measures of recharge: the case of the Table Mountain springs, Cape Town, South Africa

Roger E Diamond[1]* and Chris Harris[2]

[1]Department of Geology, University of Pretoria, Hatfield, 0028, Pretoria, South Africa; roger.diamond@up.ac.za

[2]Department of Geological Sciences, University of Cape Town, Rondebosch, 7700, South Africa; chris.harris@uct.ac.za

* author for correspondence

ABSTRACT

Tracing the flow of groundwater with little hydrochemical variability over short distances is challenging. Stable isotopes offer a solution where there is considerable variation in relief. This study used stable isotopes to delineate recharge areas and pinpoint the aquifer responsible for the many springs that issue from the lower slopes of Table Mountain in South Africa. Table Mountain rises 1086 m above sea level (masl) and, like the surrounding south-western Cape region, experiences a Mediterranean climate. The stable isotope composition of rainfall and springs issuing from the lower slopes was measured over the 2010-2012 period, allowing comparisons over space and time. An amount effect, an altitude effect (δD = -0.48‰/100 m, $\delta^{18}O$ = -0.075‰/100 m) and significant interannual variations (year to year ~10‰ δD and ~1‰ $\delta^{18}O$) in isotope composition of rainfall were observed. This enabled estimation of the average altitude of recharge to be ~300 masl, which indicates that the spring sources are aquifers comprising the scree aprons ringing the mountain, with an average groundwater flow path of about a kilometre. Matching the shifts in average annual isotope composition and deuterium excess of the springs with that of nearby rainfall suggests that some groundwater flow is fast: recharge to discharge within months. However, steady discharge rates over seasons and years indicate that flow is generally slow. Hence, a hydrogeological model is proposed with fast, recent water flowing in shallow parts of the aquifer at the same time as slow, older water in deeper parts of the aquifer.

KEYWORDS:

South Africa; stable isotopes; springs; groundwater flow; recharge.

1 Introduction

The H- and O-isotope composition of water varies as it moves through the water cycle, influenced by processes such as evaporation, condensation and rainout, and by the conditions under which these occur, such as temperature, humidity and windspeed (Gat & Gonfiantini, 1981). Variations in the stable isotope composition of water have been used to help understand a variety of scientific questions, such as moisture source region (Peng et al. 2010), types of weather systems generating precipitation (Kurita 2013), determining groundwater recharge area (Diamond & Harris 2000) and types of weather events responsible for groundwater recharge (Vogel & Van Urk 1975).

Studies of springs make use of many tracers, for instance injected salt (Caballero et al. 2002), or naturally occurring or ubiquitous substances such as tritium and helium (Rademacher et al. 2001) or sulphate (Guglielmi et al. 2000), to understand groundwater flow or to determine the average

age since recharge of the water. Stable isotopes are also frequently used in understanding the hydrogeology of springs. Spring water types can be differentiated and hydrogeological compartments identified on the basis of variations in isotope compositions (Larsen et al. 2001). Seasonality can be detected with cyclic stable isotope compositions of spring discharge, suggesting fast groundwater transit (Plummer et al. 2001). The nature of previous climates can be gauged from shifts in mean hydrogen and oxygen isotope composition between young (current climate) and old spring waters (Sidle & Cvetic 2011).

More locally, a study of the thermal springs in the Cape Fold Belt in South Africa, of which Table Mountain is found at the very south-western extremity, was conducted by Diamond & Harris (2000). By comparing the stable isotopes of precipitation with those emerging at the thermal springs, they concluded that groundwater flow paths were regional, with recharge in high mountains several kilometres away (at least) from the springs. Also locally, and more recently, Miller et al (2017) used stable isotopes, in conjunction with noble gases, to elucidate some aspects of the groundwater recharge and flow system for springs in the Table Mountain Group near Paarl, about 60km from Cape Town. Their results suggested steady recharge from most of the rainfall, in close proximity to the springs, with little evaporative enrichment of stable isotopes prior to recharge.

1.1 Previous work and objectives

In spite of the importance of the Table Mountain springs supplying perennial water to the area and therefore determining human habitation of the area for millenia (Brown & Magoba 2009, p55), very little scientific work has been done on this groundwater resource. No geophysical investigations have been done over the area, no boreholes have been drilled where they could supply information on the aquifer feeding the springs, and only minor investigations on flow rate and water quality have been done over the years (e.g. Conrad et al. 2013), mostly contained in technical reports or other literature that is no longer accessible. Hydrogen and oxygen isotopes of water were assessed as a method to investigate the hydrogeology, commencing with an assessment of precipitation (Diamond & Harris 1997). This study monitored rainfall over 1995-1996 at Cape Town, Tulbagh, Citrusdal and Oudtshoorn, covering the Western Cape, and produced the first meteoric water line for the region ($\delta D = 6.1\delta^{18}O + 8.6$). Harris et al (2010) continued measuring precipitation at University of Cape Town (UCT) and produced a similar meteoric water line for 1995-2008 ($\delta D = 6.41\delta^{18}O + 8.66$), as well as beginning to sample the springs around Table Mountain, which entailed re-discovering these almost forgotten water resources, as many of the springs are now inaccessible on private property, buried under buildings or piped directly into the stormwater system.

Harris et al (2010) found that although the annual mean stable isotope composition of precipitation varied, there was no systematic trend over the years, nor any clear correlation with annual air temperature or precipitation amount. Springs were monitored for their stable isotope composition sporadically, but appeared to show some similarities in shifts to that of the precipitation, leading the authors to the conclusion that groundwater throughput is fast and perhaps 50% of the aquifer volume is recharged in three years.

The aim of this study was to use stable isotopes of hydrogen and oxygen in the spring discharge and rainfall to look for patterns that might reveal the hydrogeological dynamics of the springs. In particular, the aim was to determine whether the Peninsula Formation quartzites of the Table

Mountain Group form part of the aquifer feeding the springs, as is the currently held belief (Conrad et al. 2013; Wu 2008; Compton 2004).

This paper describes the springs in general before providing an overview of the geology and climate. The methods, including field and laboratory procedures are covered in brief, after which the results are presented, including tables of raw data. The data are then interpreted and discussed, to provide insight into the recharge, aquifer and groundwater flow system of the springs.

2 Table Mountain Springs

Several springs issue from the lower slopes of Table Mountain, and they are characterized in two clusters: the City Bowl cluster and the Newlands cluster. These springs have influenced the ecology and human development in the region, including the significant historical decision to site Cape Town in 1652 in its present position, rather than at Saldanha Bay with its better harbour (see Figure 1), but without a permanent source of fresh water (Brown & Magoba 2009, p55). The springs sampled as part of this project, which include all the major springs and some of the minor ones, in terms of flow, are listed in Table 1 and shown in Figure 2. Many springs, especially those at lower altitude, have been capped and diverted to stormwater, irrigation or industrial use, although in some cases overflows or valves allow access for sampling. Some of the springs are perennial and maintain relatively steady flow over the dry season and through drought years, whereas others are seasonal.

Table 1: Sampling sites for springs and rain.

site name	coordinates		elevation	flow
	northing	easting	(masl)	(approx. L/s)
Newlands cluster (springs)				
Wendy's	33.9634°S	18.4436°E	310	1
Redwood	33.9726°S	18.4387°E	270	1
Kirstenbosch	33.9893°S	18.4288°E	160	2
Princess Anne	33.9642°S	18.4587°E	90	0-5
Kommetjie	33.9703°S	18.4532°E	75	7
Newlands	33.9746°S	18.4577°E	35	30
Palmboom	33.9737°S	18.4590°E	35	3
Albion	33.9670°S	18.4675°E	15	11
City Bowl cluster (springs)				
Lily Pond	33.9575°S	18.4039°E	900	0.01
Tafelberg Road	33.9549°S	18.4261°E	410	0-1
Cableway	33.9488°S	18.4067°E	320	0-1
Rugby Road	33.9478°S	18.4131°E	230	1
Glencoe	33.9439°S	18.4050°E	220	0.5
Stadsfontein	33.9419°S	18.4155°E	115	25
Leeuwenhof	33.9386°S	18.4066°E	110	3
Rain				
University of Cape Town	33.9588°S	18.4604°E	135	-
Upper Cableway Station	33.9574°S	18.4028°E	1074	-
Wolfkop Nature Reserve	32.6387°S	19.0556°E	355	-
Uitkyk Pass	32.4041°S	19.1150°E	1013	

The springs are in order of decreasing altitude and split into Newlands and City Bowl groups. The flow rates are estimates, using a bucket and timer, and because flow varies at the springs and some are non-perennial, they are indicated by a flow rate from zero.

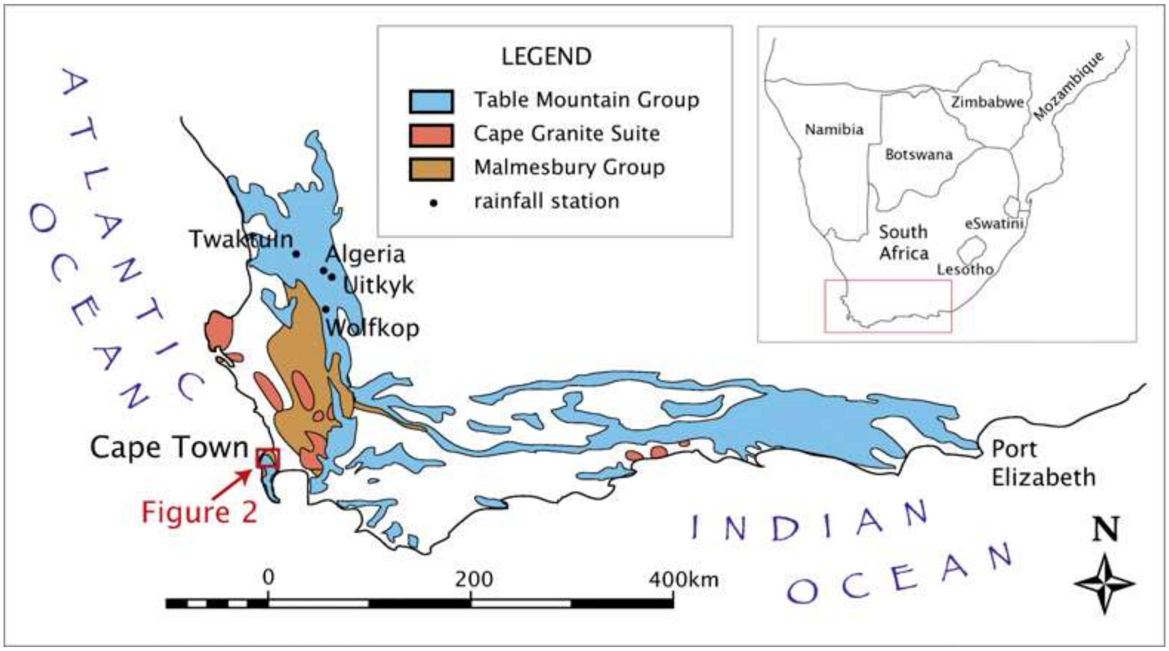

Fig. 1. Regional geology and location of outlying rainfall stations

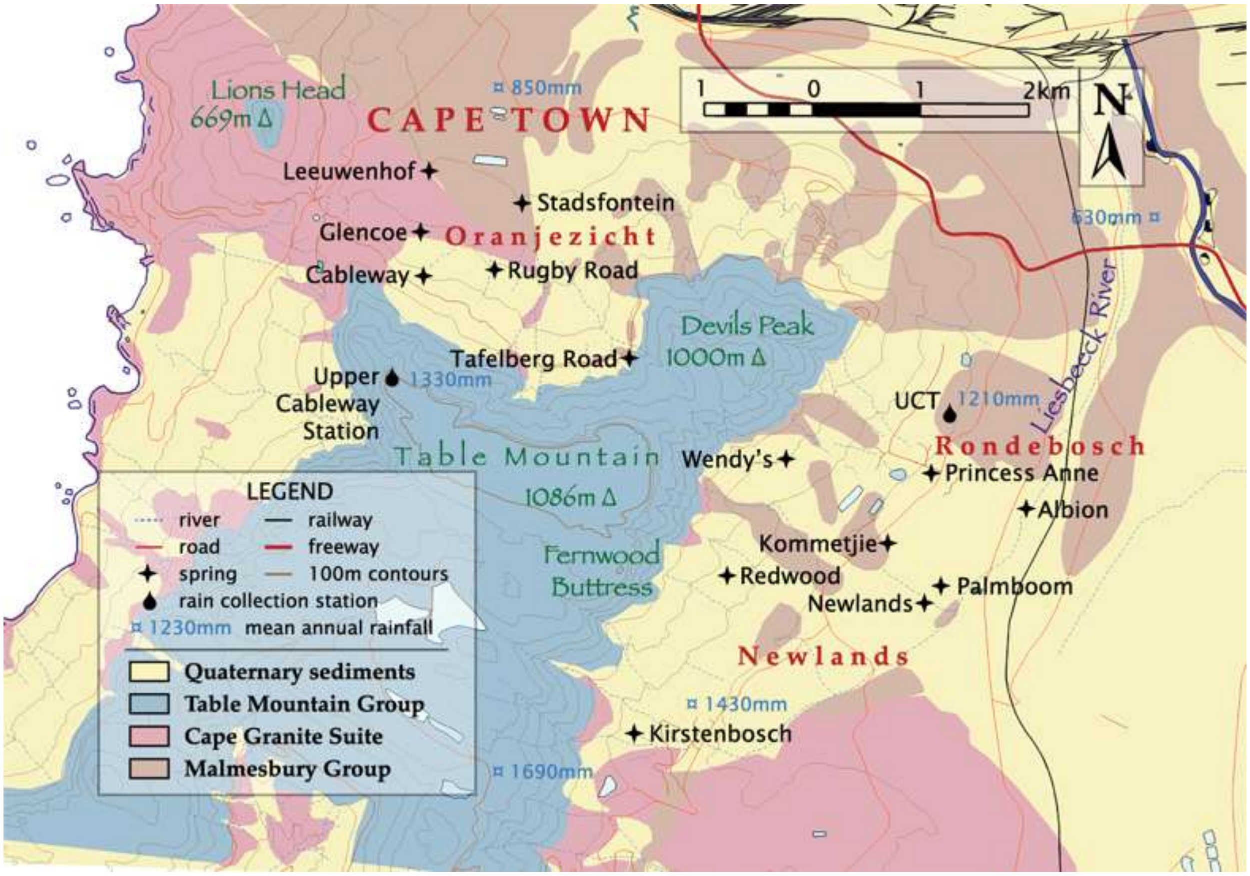

Fig. 2. Map of the study area, including topography, geology, springs, rainfall collection stations, mean annual rainfall amounts for weather stations (SAWB 1996 and this study) and other features

Water quality, in terms of drinking, at all of the springs is very good, with total dissolved solids values ≤ 100 mg/L (Conrad et al. 2013). There is little variation in the water chemistry, all waters being Na-Cl dominated, and detailed interpretation of the small variations would be hampered by the presence of pipes, collection chambers and other structures between the point of access for sampling and the natural discharge zone (Conrad et al. 2013). These structures could either contaminate the water directly or allow modification of the true groundwater composition through settling or oxidation.

3 Geology, Climate and Hydrogeology

Table Mountain rises to 1086 m above sea level (masl) and is composed of the stratiform Ordovician Table Mountain Group which unconformably overlies deformed metasediments of the Late Precambrian Malmesbury Group. The Malmesbury Group in the region (Figure 1) was intruded by granites of the Cape Granite Suite (552-515 Ma, Scheepers & Armstrong, 2002). The Peninsula Granite has a zircon U-Pb age of 540 ± 5 Ma (Scheepers and Armstrong 2002; Villaros et al. 2011), and underlies most of Table Mountain (Fig. 1). The base of the Table Mountain Group here comprises maroon siltstones and mudstones with minor sandstones of the Graafwater Formation. This is overlain by uniform, thickly bedded, quartzitic sandstones of the Peninsula Formation. The Table Mountain Group is highly fractured (mostly horizontal bedding planes and vertical joints) and very well exposed on the upper slopes, with many cliffs in the Peninsula Formation. The lower slopes are largely covered by scree, dominated by boulders derived from the Peninsula Formation, and soils, overlying weathered materials of the Graafwater Formation, Cape Granite and Malmesbury Group (Theron et al. 1992). No work has been done on the screes around Table Mountain, although some work was done on screes in the Hex River Mountains of the Cape Fold Belt (Boelhouwers 1993), about 100 km to the north-east of Cape Town. This work concluded, along with previous opinion, that the screes are a product of the wetter and colder climate that existed in the Pleistocene, and are largely inactive today, being steadily colonized by vegetation and resultant soil.

The climate of Cape Town is Mediterranean, with cold wet winters and warm dry summers. A typical summer day in January has mean minimum to maximum temperatures of 16-26 °C compared to 7-17 °C for winter in July. Rainfall varies widely in the microclimates around Table Mountain. Most rain occurs in the 6 months from May to October and approaches from a north-westerly, westerly or south-westerly direction. Because of the small size of Table Mountain and the turbulence it creates in the stratified maritime airflow, the mountain triggers rain and the highest rainfall amounts are recorded downwind of the mountain, on the eastern side. Areas close to the mountain on the downwind side have average rainfall amounts from 1600 mm/a at Kirstenbosch to 1200mm/a at the University of Cape Town (SAWB 1996 and this study). At similar altitude and distance from the mountain, but on the upwind side in Oranjezicht (near the city centre) an average of 800 mm/a is measured, whereas 15 km away to the east, at the airport, an average of only 540 mm/a is recorded (CSAG 2013, SAWB 1996).

Rain around Cape Town can be caused by any one of 5 different weather systems: 1 westerly wave, 2 southerly meridional flow, 3 ridging anticyclone, 4 cut-off low, 5 west coast trough (Preston-Whyte & Tyson 1988, SAWB 1996). The first two of these cause the majority of rain in Cape Town, especially during winter, whereas the other three, although capable of producing significant rain events, are generally uncommon. The westerly wave is a cold-front type system, also known as a mid-latitude cyclone, and produces steady widespread rain that can be light to heavy, for anything from a few hours to a day or so. The southerly meridional flow occurs after the passage of the westerly wave and brings cumulus clouds that cause showers, often known as "clearing showers", because of the appearance of intermittent blue sky after the overcast conditions of the westerly wave. This rain is typically heavy, and although each shower only lasts several minutes to an hour or so, the entire period of southerly meridional flow can last up to about two days.

Groundwater on Table Mountain occurs in two main aquifers. The Table Mountain Group, although thoroughly cemented, is highly fractured (Lin et al. 2007), and the quartzites of the Peninsula Formation make up a secondary porosity aquifer that is capable of high yields (>10 L/s) in boreholes and from springs (Hartnady & Hay 2002). On the flanks of the mountain are scree slopes, mainly made up of boulders of Table Mountain Group quartzite, and along with the weathered profiles of the granite and metamorphic rocks make up primary porosity aquifers. These units are discontinuous and poorly understood, with only their approximate areal extent having been mapped geologically (Geological Survey, 1990). No data exist on thicknesses or on any hydraulic parameters.

4 Methods

Rainfall was collected at six stations: on the roof of the Department of Geological Sciences at UCT at 135 masl; on the roof of the Upper Cableway Station on top of Table Mountain (TMC), at 1074 masl; at Wolfkop Nature Reserve near Citrusdal; at Twaktuin Farm near Clanwilliam; and at Algeria and Uitkyk Pass, both in the Cederberg (Figures 1 & 2). The amount of rain was measured using a standard rain gauge with millimetre graduations, which was emptied every morning, and the rainfall amount recorded. The sampling methodology is described in detail in Harris et al. (2010). When emptying rain gauges on a daily schedule, evaporation is generally insignificant. Some rainfall amounts were not recorded and these have been estimated by using nearby rainfall stations from this project and the South African Weather Service (SAWS). The estimation was performed in a spreadsheet, using data from stations within a 50km radius, to generate an average of the nearby stations, and correct for the known difference between the station with the missing data and the stations with data. SAWS stations used were Kirstenbosch and Molteno for the Table Mountain Cableway, and Redelinghuys, Clanwilliam and Excelsior for Uitkyk Pass and Wolfkop. Spring water was collected from the springs listed in Table 1 twice per year in 2010-2012, generally at the end of the dry season, around April, and at the end of the wet season, around November. The Stadsfontein spring was sampled from a collection chamber near the spring that includes water from other springs in the area, such as Rugby Road.

The water was prepared for stable isotope analysis by equilibration with CO_2 for oxygen isotopes, using the method of Socki et al. (1992), and reaction with Zn for hydrogen isotopes (Tanweer et al. 1988), and then analysed in a DELTAplus XP stable light isotope ratio mass spectrometer (2004 Thermo Corporation). Drift in the mass spectrometer reference gases was corrected for with the use of two internal standards, whose δ values are known. The mean difference in replicates of the standards during sample runs is 0.2‰ for $\delta^{18}O$ and 1‰ for δD, which represents the analytical precision. The isotope composition of hydrogen or oxygen in water is displayed as a deviation in thousandths (δ ‰) from the Standard Mean Ocean Water reference (SMOW), as follows:

Table 2: Actual and estimated(*) rainfall amounts.

year/month	rainfall (mm)					
	UCT	TMC	Uitkyk	Wolfkop	Twaktuin	Algeria
2010/01	9	*10	*5	*0	0	-
2010/02	13	*20	*40	*10	15	-
2010/03	7	*10	*5	*0	0	-
2010/04	45	*60	*20	*5	11	-
2010/05	275	280	100	170	144	-
2010/06	201	*170	*200	154	90	-
2010/07	166	200	112	64	36	-
2010/08	121	150	215	84	69	-
2010/09	101	100	*80	30	54	-
2010/10	103	*120	*70	28	55	-
2010/11	73	90	95	*10	12	-
2010/12	17	60	105	*80	57	-
2011/01	16	*30	20	*10	0	-
2011/02	3	*20	30	*10	0	20
2011/03	16	*50	20	*10	4	16
2011/04	111	*90	65	*20	18	-
2011/05	145	142	340	*150	125	128
2011/06	191	*150	440	*180	144	140
2011/07	49	70	94	*50	45	74
2011/08	209	165	270	*80	73	106
2011/09	141	115	*60	*30	34	-
2011/10	41	100	65	*40	42	45
2011/11	72	*100	25	*20	28	-
2011/12	62	*90	10	*10	11	15
2012/01	46	130	*0	*5	0	-
2012/02	21	80	*0	*5	0	-
2012/03	69	*110	30	*20	20	29
2012/04	133	*130	60	*30	27	77
2012/05	143	155	*90	*20	37	20
2012/06	230	*200	*400	*120	156	190
2012/07	300	*240	200	*80	43	72
2012/08	214	145	140	*100	118	-
2012/09	172	215	*80	*50	47	-
2012/10	44	123	*30	*20	15	-
2012/11	60	44	*5	*0	0	-
2012/12	10	*20	*10	*0	0	-

UCT= University of Cape Town, TMC= Upper Cableway Station on top of Table Mountain

Estimations made use of nearby SAWS stations, as well as the data from Twaktuin and Algeria, collected for this study (see text in the Methods section).

$$\delta = (R_{\mathrm{sample}} - R_{\mathrm{standard}})/R_{\mathrm{standard}} \qquad (1)$$

where R is the isotope ratio (D/H or $^{18}O/^{16}O$).

Rainfall amounts (Figure 3) were also recorded for use in determining the weighted annual mean isotope composition.

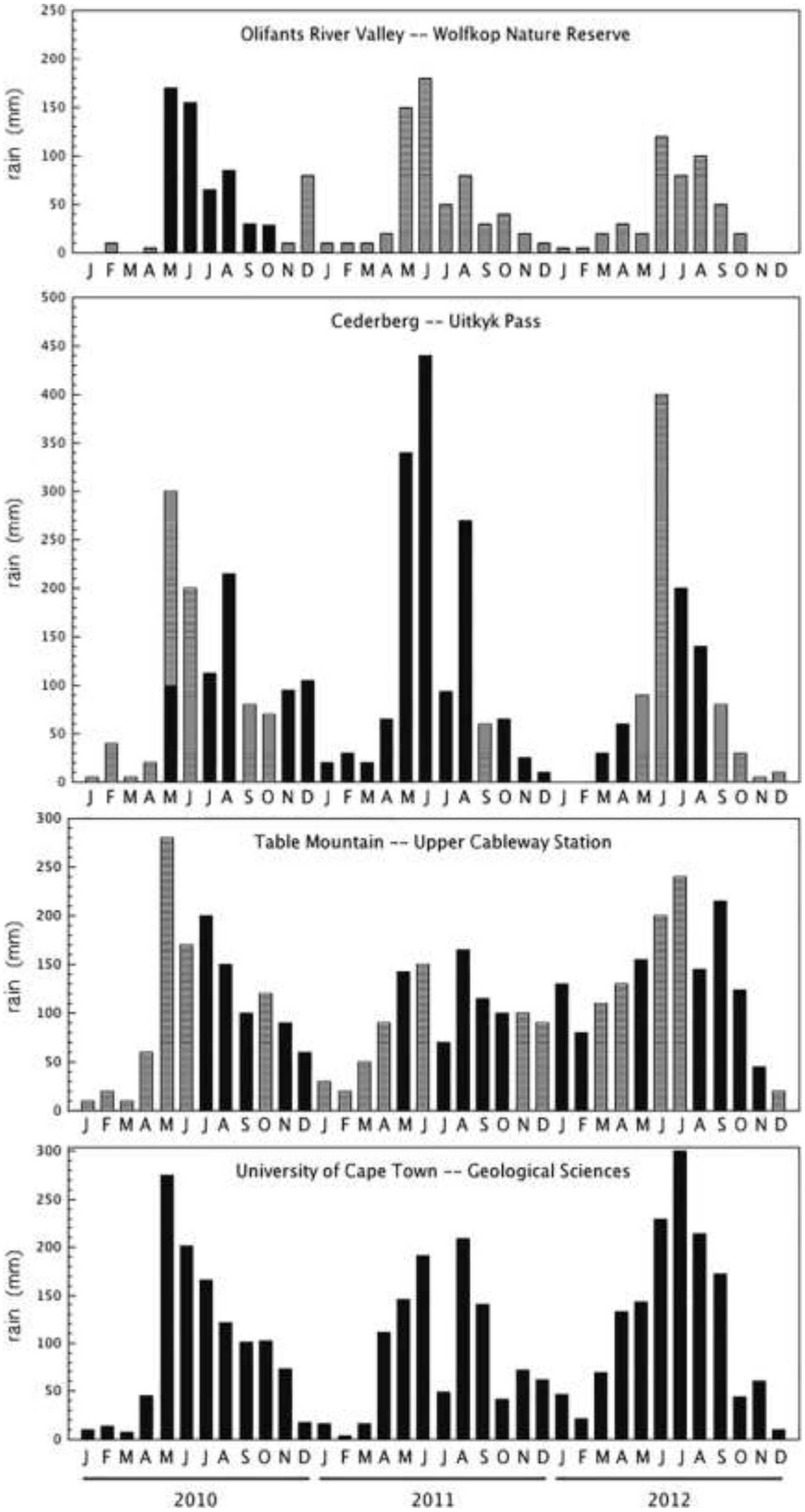

Fig. 3. Rainfall records for the rain collection stations. Black bars are actual measurements; grey bars are estimates, based on nearby weather stations and corrected for local differences (see text in the 'Methods' section)

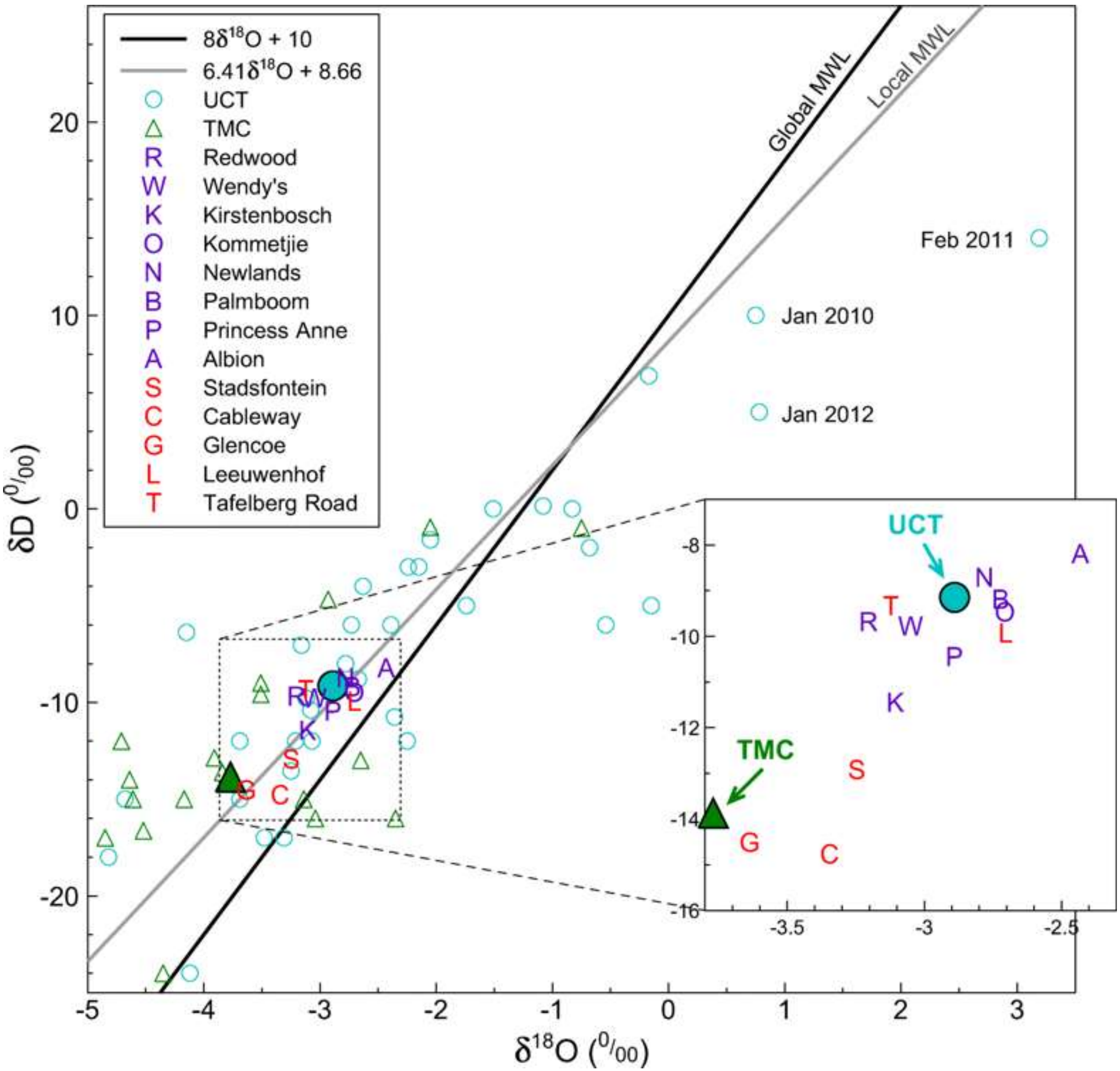

Fig. 4. δD-δ^{18}O diagram showing all data for UCT and TMC rain collection stations in 2010–2012, as well as their weighted means (indicated with arrows), plus means of all springs (as letters), and meteoric water lines (MWL). City Bowl cluster of springs shown in red, and Newlands cluster shown in purple. Global MWL from Craig (1961). UCT University of Cape Town; TMC Upper Cableway Station on top of Table Mountain

5 Results

All the monthly rain samples and the weighted 2010-2012 means for the two rainfall stations are plotted in Figure 4. Also shown are mean values for each spring, based on the samples taken over the three year period. The LMWL, with equation $\delta D = 6.41\delta^{18}O + 8.66$, was calculated by Harris et al. (2010) for the UCT station over 1995-2008 and is in agreement with the equation from Diamond & Harris (1997) who used 4 stations around the Western Cape over 1995-1996 ($\delta D = 6.1\delta^{18}O + 8.6$). Meteoric water lines were calculated by reduced major axis regression, which assumes error in both x and y variables, and is therefore more suited to stable isotope data than the more commonly used least squares regression (Rock, 1988).

The high δ-value rainfall samples from UCT (Figure 4) are all for months with low rainfall, and show the evaporative enrichment in heavy isotopes typical of summer rain in a Mediterranean climate (Argiriou & Lykoudis 2006). The TMC station does not show this because of the much shorter raindrop pathway through the atmosphere in which evaporation can take place.

An altitude effect (Dansgaard 1964; Gat 1996) can be calculated for Table Mountain using the altitude difference between the UCT and TMC rainfall stations. The gradients are:

$\delta D = -0.48‰/100$ m

$\delta^{18}O = -0.075‰/100$ m.

These are at the low end of the range of altitude effects measured elsewhere in the Cape Fold Mountains by Diamond & Harris (2019), who found gradients of -1.8‰ and -1.6‰/100 m for δD and -0.33‰ and -0.34‰/100 m for $\delta^{18}O$ in the Little Karoo and Hex River Valley respectively, and by other workers (Clark & Fritz 1997; Gonfiantini et al. 2001; Ladouche et al. 2009). This is possibly because the lower altitude station, UCT, is inland of TMC and therefore the continental effect lowers the δ values of precipitation at UCT, which is the opposite of typical altitude effect studies where rainout (and hence lower δ values) from increasing altitude coincides with rainout from increasing continentality.

There appears to be an isotope gradient in spring water away from Table Mountain, that is possibly attributable to an amount effect (Figure 5); This will be discussed further below. Analysis of long term (>10 a) rainfall isotope composition at UCT reveals there are changes in the annual weighted mean from year to year (Harris et al. 2010), as seen in Figures 6 and 7. This was attributed by these authors to climate factors at both the Cape Town area, and the site of evaporation. Cape Town receives rainfall that is dominantly sourced from the Atlantic Ocean to the west, but mixing with rainfall sourced from the east is another potential cause of isotope variation. Exact explanations are beyond the scope of this paper, but in any case do not matter for the major aim of this paper, which is to compare and interpret the pattern of changes in the isotope composition of rainfall and spring water. The TMC station shows changes in rainfall isotope composition from 2010-2012 that are identical in direction on Figure 6, but greater in magnitude than rainfall at UCT (Fig. 6). Two other rainfall stations in the western part of the Western Cape, with similar climate to Cape Town, show similar shifts in isotope composition: Wolfkop Nature Reserve (5 km south of Citrusdal) and Uitkyk Pass (in the Cederberg), which are 150 and 180 km from Cape Town, respectively, in a NNE direction.

When the spring data for Cape Town are plotted by year (Figure 6), although there is overlap in the data, there are differences in mean isotope composition of discharge from the springs in different years. The pattern of changes in the mean isotope compositions for each year's spring data during 2010 to 2012 has a remarkable similarity to that observed in rainfall over the same period (Figure 7). The data were analysed in detail by separating springs into groups based on seasonal or perennial, high or low flow, altitude and Cape Town or Newlands clusters, yet there was no clear pattern. It is only when all the springs were lumped together that the pattern of interannual change in stable isotope composition mimics that in the rainfall (Tables 3 and 4).

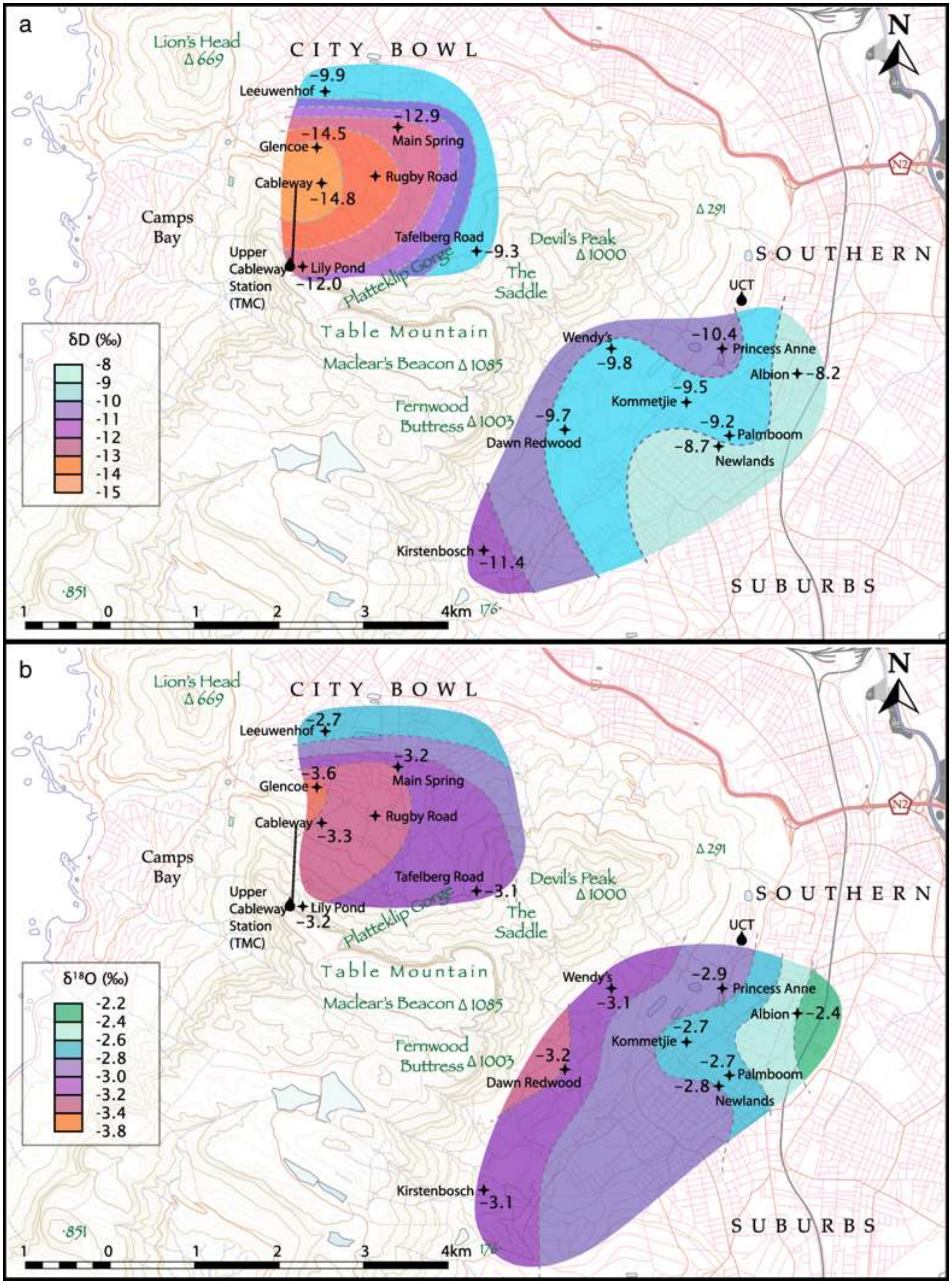

Fig. 5. Contours of **a** hydrogen and **b** oxygen isotope compositions for the springs. The extent of the coloured contoured areas is determined by the extent of the springs. There is insufficient data to join the two areas, mainly due to a lack of springs to sample

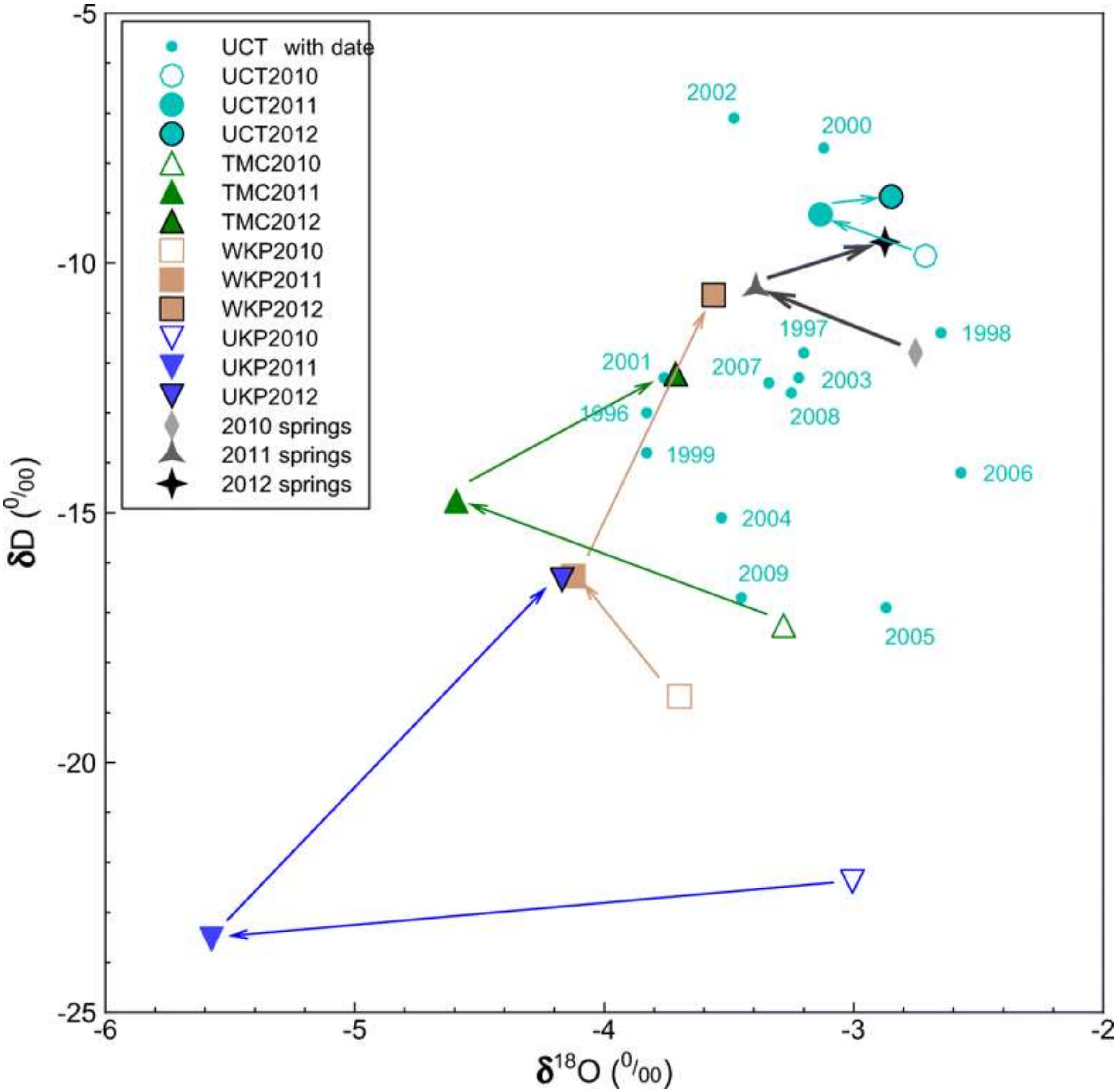

Fig. 6. δD-δ^{18}O plot of water samples from 13 springs around Cape Town labelled according to year of sampling, revealing the interannual variations in isotope composition

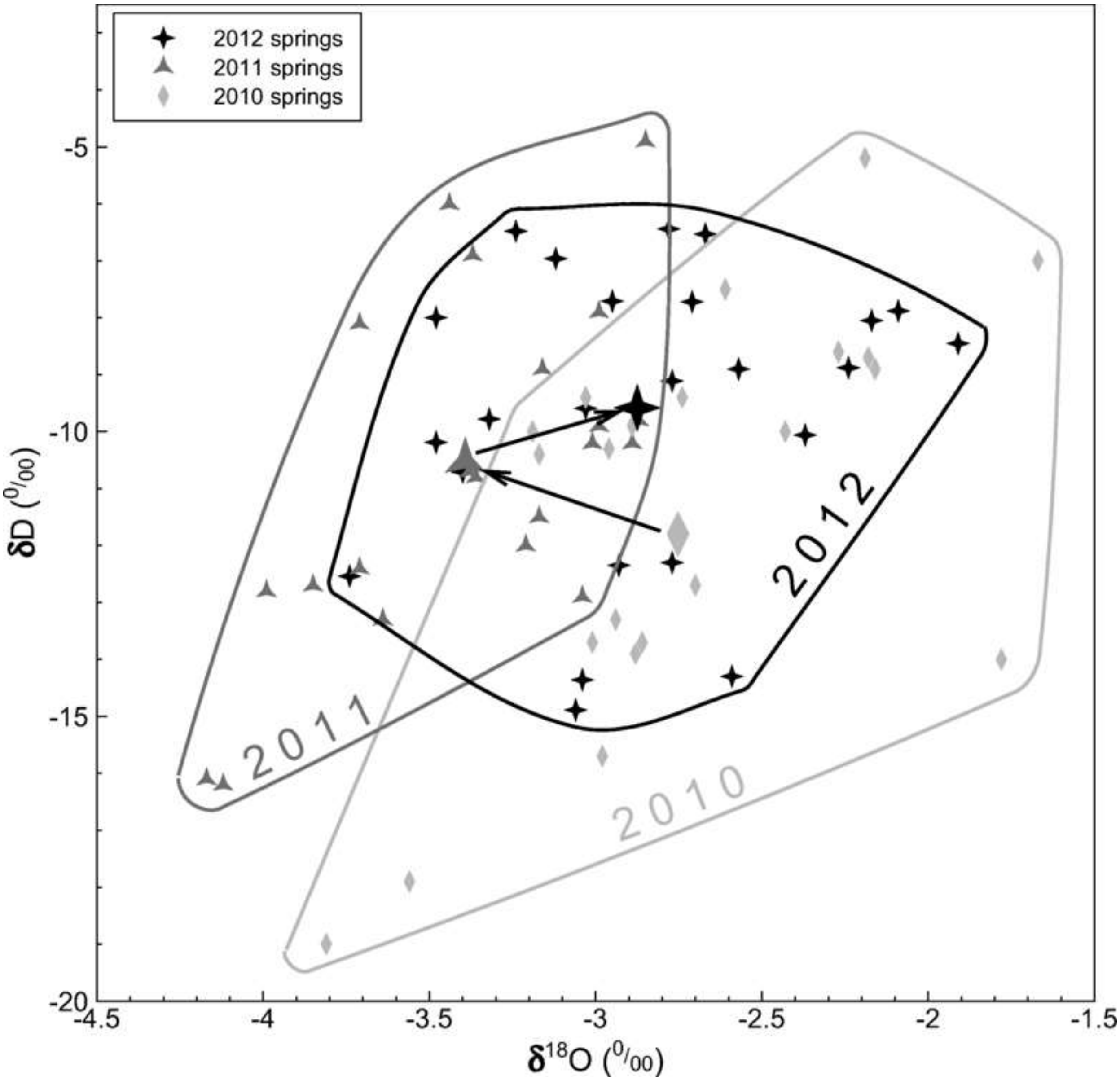

Fig. 7. δD-δ^{18}O plot of weighted annual isotope composition of springs and precipitation. Arrows show progression for means in 2010–2011–2012. Rain data prior to 2009 from Harris et al. 2010

Table 3: Stable isotope composition of cumulative monthly rainfall samples.

month	2010		2011		2012	
	δD (‰)	**δ^{18}O (‰)**	**δD (‰)**	**δ^{18}O (‰)**	**δD (‰)**	**δ^{18}O (‰)**
University of Cape Town						
J	9.7	0.75	-5.2	-0.15	5.4	0.78
F	-5.8	-0.54	13.9	3.19	-2.5	-0.68
M	0.4	-0.83	-23.6	-4.12	-11.9	-3.07
A	-12.1	-2.25	-5.8	-2.73	-9.8	-3.12
M	-8.4	-2.78	-12.3	-3.69	-10.4	-3.08

J	-17.0	-3.31	-18.3	-4.82	-6.4	-4.15
J	-15.0	-3.69	-14.6	-4.68	-8.8	-2.67
A	-4.9	-1.74	-3.8	-2.63	-13.5	-3.25
S	-3.3	-2.24	-0.1	-1.51	-10.8	-2.36
O	-3.3	-2.15	-17.0	-3.48	-7.1	-3.16
N	-6.2	-2.39	-12.0	-3.21	0.1	-1.08
D	-39.9	-5.06	-1.6	-2.05	6.9	-0.17
Table Mountain Cableway						
J	-	-	-1.2	-0.75	-4.7	-2.93
F	-	-	-	-	-1.0	-2.05
M	-	-	-	-	-12.9	-3.91
A	-	-	-14.8	-4.61	-13.7	-4.34
M	-15.0	-3.14	-14.7	-4.17	-	-
J	-24.4	-4.35	-16.9	-4.85	-8.7	-2.32
J	-	-	-11.6	-4.71	-7.6	-2.93
A	-	-	-14.4	-4.64	-20.8	-4.82
S	-	-	-9.2	-3.51	-22.4	-5.75
O	-16.3	-3.04	-13.6	-3.84	-	-
N	-13.1	-2.65	-17.4	-4.64	-	-
D	-16.0	-2.35	-9.6	-3.51	-	-
Wolfkop Nature Reserve						
J	-	-	-	-	-	-
F	-	-	-15.1	-3.13	-	-
M	-	-	-41.4	-4.13	-30.8	-5.49
A	-	-	-11.2	-4.07	-10.2	-3.16
M	-11.7	-2.57	-16.0	-4.10	10.9	-1.12
J	-25.8	-4.77	-15.0	-4.00	-15.9	-4.40
J	-14.7	-3.82	-30.4	-6.06	-4.8	-2.65
A	-1.5	-1.55	-14.6	-4.17	-9.4	-3.51
S	-24.1	-4.21	3.5	-1.54	-	-
O	-0.9	-1.60	-11.8	-3.06	-	-
N	2.2	-0.56	-40.0	-7.94	-	-
D	-47.8	-7.12	-1.1	-2.11	-	-
Uitkyk Pass						
J	-	-	-	-	-	-
F	-	-	-	-	-	-
M	-	-	-29.2	-5.35	-33.3	-5.57
A	-	-	-22.7	-5.79	-15.6	-4.05
M	-	-	-22.4	-5.46	-0.5	-1.82
J	-	-	-24.9	-5.85	-	-
J	-	-	-23.9	-5.85	-18.3	-4.37
A	-16.6	-3.53	-20.2	-5.21	-20.5	-5.14
S	-18.2	0.97	-	-	-	-
O	-1.0	3.43	-30.3	-5.13	-	-
N	-17.4	-3.12	-23.2	-4.94	-	-
D	-56.2	-9.14	-7.6	-4.17	-	-

Table 4: Isotope data for the Table Mountain springs.

Site name	2010-2003		2010-2011		2011-2005		2011-2010		2012-2005		2012-2009	
	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)
Newlands cluster												
Wendy's	-	-	-9.4	-2.74	-	-	-10.7	-3.38	-9.8	-3.32	-9.1	-2.77
Redwood	-	-	-10.3	-2.96	-	-	-10.8	-3.36	-8.0	-3.48	-9.6	-3.03
Kirstenbosch	-13.7	-3.01	-9.4	-3.03	-12.4	-3.71	-12.9	-3.04	-10.2	-3.48	-10.1	-2.37
Princess Anne	-	-	-	-	-	-	-12.0	-3.21	-	-	-8.9	-2.57
Kommetjie	-13.9	-2.88	-8.9	-2.16	-8.9	-3.16	-10.2	-2.89	-6.5	-3.24	-8.5	-1.91
Newlands	-13.3	-2.94	-7.5	-2.61	-6.9	-3.37	-10.2	-3.01	-6.5	-2.67	-7.9	-2.09
Palmboom	-13.7	-2.86	-10.0	-2.43	-4.9	-2.85	-9.9	-2.99	-7.7	-2.95	-8.9	-2.24
Albion	-8.7	-2.18	-7.0	-1.67	-7.9	-2.99	-9.8	-2.87	-7.7	-2.71	-8.0	-2.17
City Bowl cluster												
Lily Pond	-	-	-8.6	-2.27	-6.0	-3.44	-12.7	-3.85	-7.0	-3.12	-12.3	-2.93
Cableway	-19.0	-3.81	-10.4	-3.17	-	-	-	-	-	-	-14.9	-3.06
Glencoe	-17.9	-3.56	-10.0	-3.19	-16.1	-4.17	-16.2	-4.12	-12.5	-3.74	-14.4	-3.04
Stadsfontein	-15.7	-2.98	-12.7	-2.70	-12.8	-3.99	-13.3	-3.64	-10.7	-3.40	-12.3	-2.77
Leeuwenhof	-14.0	-1.78	-5.2	-2.19	-8.1	-3.71	-11.5	-3.17	-6.4	-2.78	-14.3	-2.59

6 Discussion

The two relationships identified place constraints on the hydrological model for the aquifer(s). Firstly, changes in rainfall isotope composition which are mimicked by the springs, and secondly, an apparent relationship between distance from Table Mountain and isotope composition in the Newlands cluster of springs. This latter correlation is seen in the inset part of Figure 4, where the mean δ values for each spring increase with increasing distance from the mountain.

6.1 Spatial variation of spring water isotope composition

The Newlands cluster of springs are situated on the lower slopes below the east face of Table Mountain, Kirstenbosch being the most southerly and Albion the most northerly of those springs sampled. The Albion Spring (A) discharges water with the highest δ values of these springs and also happens to discharge both at the lowest altitude and furthest position from the steep cliffs and the summit near the east face of Table Mountain. The recharge area for Albion spring must receive, overall, the rainfall with the highest δD and $\delta^{18}O$ values of all the Newlands cluster of springs.

The opposite holds for Kirstenbosch (K), and to a lesser extent Redwood (R) and Wendy's (W), which have the lowest δ values and are found at both higher elevations and closer to the high cliffs of Table Mountain. The sequence of springs, from most negative to most positive δ values is:

Kirstenbosch (K) → Redwood (R) & Wendy's (W) → Princess Anne (P) → Kommetjie (O) & Palmboom (B) & Newlands (N) → Albion (A).

For all of the Newlands cluster of springs, the position of the spring waters on the δD–$\delta^{18}O$ graph roughly corresponds to the geographic position, resulting in a sequence from more to less negative δ values as the springs are located further from the high cliffs at the southern end of the east face of Table Mountain around Fernwood Buttress.

It is postulated that this trend reflects an amount effect (e.g. Uemura et al. 2012), as the Fernwood Buttress and Kirstenbosch areas receive the highest rainfall in Cape Town, with the rainfall amount decreasing steadily with distance from this area. Increased rainfall amounts reduce the amount of evaporation taking place on raindrops as they fall, limiting evaporative enrichment, and bigger rainfall events require condensation of progressively more isotopically negative vapour, as the isotopically heavier rain has already fallen.

The correlation between δ values and distance from Table Mountain is consistent with a relationship between the position of a spring and its recharge area. This means groundwater flow on the km scale is unlikely to occur, because recharge and discharge areas are close. It also means that whatever the distance between a spring and its recharge area, a similar distance exists for all the springs, to account for the pattern seen in Figure 4. If some springs were fed by long-distance groundwater flow, they would probably not sit neatly into the observed trend. The weighted average for UCT rainfall lies very close to many of these springs, especially Wendy's, Princess Anne, Newlands, Palmboom and Kommetjie, which are geographically also close to UCT. All this evidence points to local recharge on the lower slopes of the mountain, with individual aquifers. The most likely aquifer for these springs is the scree and weathered material overlying the basement. The Table Mountain aquifer is unlikely to be directly involved, because it would result in similar delta values in all springs.

There is no correlation between $\delta^{18}O$ and altitude on the northern side of Table Mountain. The Lily Pond seep was sampled in summer and therefore may have experienced enough evaporation to cause a shift to less negative δ values. The Tafelberg Road spring is probably recharged at lower elevation than the other springs in a local scree slope that is not fed with water from the high cliffs of Table Mountain and so also has relatively less negative δ values. These factors complicate interpretation of the isotope composition of the City Bowl springs. However, the Lily Pond is only a seep and Tafelberg Road spring is non-perennial, and so if the data from these springs are to be excluded from the analysis, the pattern for the City Bowl springs becomes more similar to that of the Newlands cluster; in other words, increasing delta values with increasing distance from the mountain.

6.2 Temporal variation in spring water isotope composition

The lack of monthly monitoring in this study precludes the detection of seasonal isotope composition changes, but, as noted above, a shift in isotope composition from year to year is found in both the rainfall and spring samples (Figures 6 & 7). This similarity confirms the initial findings of Harris et al (2010), that groundwater circulation is rapid, with a major percentage of water being discharged in the same season it was recharged.

The average δD and $\delta^{18}O$ values of the springs as a whole (-10.6‰ and -3.0‰, respectively) are more negative than the average rainfall over the same period at UCT (δD = -9.1‰; $\delta^{18}O$ = -2.9‰), but more positive than the average rainfall at TMC on Table Mountain (δD = -14.7‰; $\delta^{18}O$ = -3.8‰) over the same period. The reasons for this could be a combination of an amount effect, an altitude effect and selection. The amount and altitude effects are described above. Selection is the process whereby groundwater recharge occurs mainly during heavy rainfall events which are isotopically more negative due to the amount effect. This generates groundwater with more negative δ values than the weighted average of ambient precipitation (Vogel & Van Urk 1975, Dogramaci et al. 2012).

As discussed by Harris et al. (2010), near contemporaneous changes in the δD and $\delta^{18}O$ values of rainfall and spring water suggest that groundwater circulation is rapid enough that ~50% recharge can occur within the same calendar year. However, most of the springs are perennial, have steady flow rates, and continue to flow during drought years (Caron von Zeil (Reclaim Camissa) pers. comm., 2014; Marius Bonthuis (City of Cape Town) pers. comm., 2012; Paul Teuchert (South African Breweries), pers. comm., 2015). This indicates that the flow period, from recharge to discharge, must be much greater than one year. Attempts were made to separate the springs on grounds of flow rate or perenniality, but the isotope patterns were too noisy to detect any clear associations. It therefore seems there is some mechanism whereby springs can both maintain a long-term, steady discharge of older groundwater, as well as discharge of more recently recharged water, within the same rainy season. It is possible that the slower moving, deeper groundwater is recharged more by very heavy rainfall events or periods, and therefore an even more negative isotope composition could be expected than for the shallower groundwater. This, however, was not detected in this study, although more detailed future studies could explore this avenue.

Transit times of groundwater in scree deposits can be very fast, with records of as little as days (Caballero et al. 2002), although these are for coarse alpine screes or moraines. Other highly conductive aquifers, such as karst, respond to rainfall within hours, with increased flow at springs after storms (Desmarais & Rojstaczer 2002). In the latter case, piston flow was detected by monitoring electrical conductivity changes in discharge water. A piston flow model cannot account for the combination of long-term sustained discharge rates and short-term fluctuations in isotope composition that match rainfall, as seen in the Table Mountain springs. A model of groundwater flow where faster-flowing younger water lies above slower-flowing older water could account for the trends observed (Figure 8). Fast flow occurs near the water table and allows recently recharged groundwater to discharge within the same season, whilst deeper flow is slower and accounts for the resilience of the springs to droughts and seasonal rainfall. Some aquifers are known to be layered, although these are mostly caused by fresh water lying above more saline water (Dose et al. 2014). Discrete flow paths or zones were reported by Muir et al. (2011) in talus in mountain areas of the Canadian Rockies, although these lie next to each other and have different discharge points, as opposed to the proposed model here, where the aquifer appears to be vertically segregated.

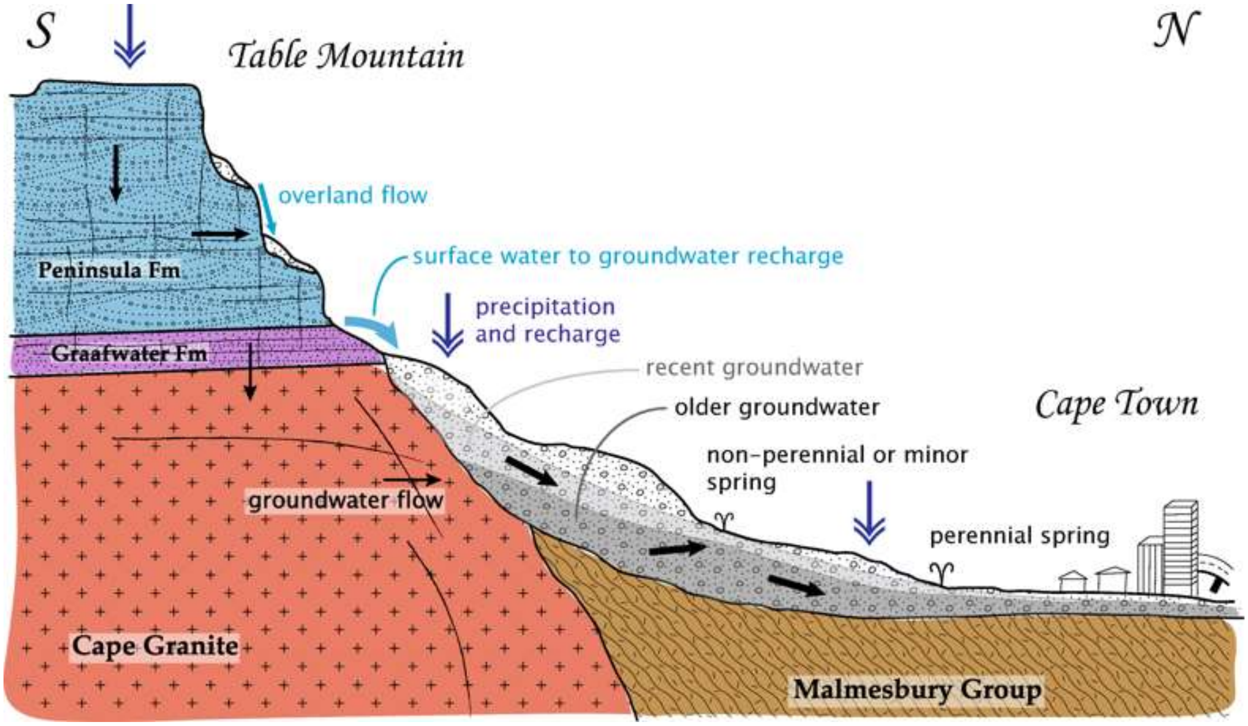

Fig. 8. Schematic diagram showing the hydrogeological setting, with the postulated layered groundwater in the scree slope aquifer, allowing for perennial and seasonal springs. The sketch shows springs on the City Bowl side of Table Mountain, but applies equally to the Newlands cluster of springs

It is not understood how groundwater flow is stratified. However, it is possible that the lower part of the scree aquifer contains more fines that have settled from above, or more weathered material from granite or metasediments that was incorporated into the lower parts of the scree during its formation. Also, when the aquifer is more saturated, the hydraulic gradient is likely to increase slightly. These scenarios could produce a variation in groundwater flow dynamics depending on how fully the aquifer is saturated. At greater saturation fractions, a higher hydraulic gradient is established in the more conductive part of the aquifer, resulting in faster flow. Such complexity within unconsolidated materials has been observed by Roy & Hayashi (2009) who stated that "unconsolidated sediment features can possess multiple, and possibly disconnected, groundwater flow paths", based on their study of talus in the Canadian Rockies.

Vitvar & Balderer (1997), using ^{18}O and Mg ions, found shallow groundwater to flow at different rates through young geological formations in Switzerland.

Comparing the results of this study to findings from other springs work in the Cape Fold Belt (Diamond & Harris 2000, Miller et al 2017, Diamond & Harris 2019) is not simple, mainly because other workers looked at groundwater systems in the Table Mountain Group and not scree deposits. However, these local studies, as well as overseas examples (Blasch & Dyson 2007), all demonstrated the viability of stable isotopes to delineate recharge on a regional to sub-regional scale (few to tens of kilometres) and aquifers on a geological formation level. This study has shown the viability, in an area of dramatic relief and isotope variability, to delineate recharge areas down to the kilometre-or-less scale, and aquifers to the within-formation level.

More detailed resolution in time is needed to understand the response of each spring to rainfall. Information on the aquifer, such as the thickness and water table depth, would also assist in developing this model. However, the available information can be used to estimate some hydrogeological parameters for the springs. Figure 9 shows how the average elevation of recharge for the springs of 316 masl has been interpolated by assuming a linear gradient for change in δ values with altitude, and assuming the differences in isotope composition are all due to altitude effects given that any amount effects are ultimately related to altitude, as rainfall amount and altitude are well correlated (Beuster et al 2009). As the mean spring elevation is 156 masl, the average difference in height between spring recharge area and discharge point is found by: 316 masl - 156 masl = 160 m. The typical ground-surface gradient on the lower slopes of Table Mountain is 9°, and so the average slope distance between recharge area and discharge point is found by: Δ*s* = 160 m / sine 9° = 1023 m. Using this average distance of about 1 km, and an estimated duration of 2-3 months between rainfall and discharge, approximate groundwater flow rates of 10-15 m/d can be calculated. These values apply to the upper portion of the aquifer where water is transferred faster than the deeper groundwater. Monthly monitoring of selected springs for their stable isotope composition will improve these estimates and the overall understanding of the hydrogeology around Table Mountain.

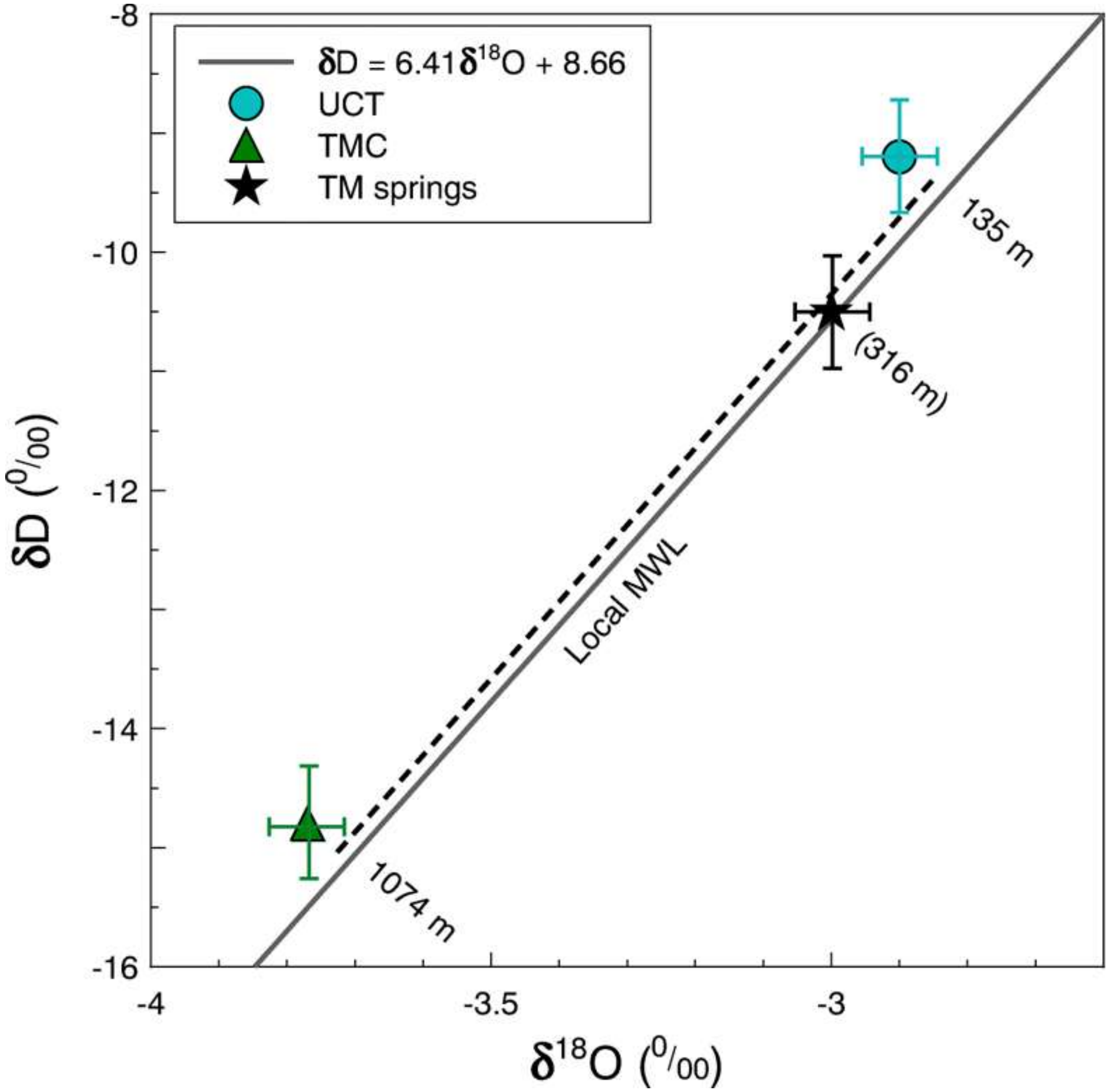

Fig. 9. Calculation of the average elevation of recharge for Table Mountain springs by interpolation between the two rainfall stations. Means for the rainfall stations are calculated from monthly isotope compositions weighted by rainfall amount. The springs mean is the arithmetic mean of all spring water isotope compositions. Error bars show analytical (laboratory) precision

7 Conclusions

An isotope altitude effect for Table Mountain has been determined, of $\delta D = -0.48‰/100$ m and $\delta^{18}O = -0.075‰/100$ m. Using this altitude effect, it has been determined that springs issuing from the lower slopes of Table Mountain are recharged at moderate elevations (around 300 masl), indicating that the aquifers conducting spring water are the scree aprons which encircle the lower slopes of the mountain. Groundwater flow paths are typically around a kilometre or so and surface water may recharge the screes where waterfalls tumble from the steeper, high part of the mountain onto the scree slopes below. An amount effect changes the isotope composition of spring water, with springs closer to the summit of Table Mountain having lower average δ values. Interannual changes in the mean isotope composition of rainfall have been observed and these changes are similar at 4 different rainfall stations in the western arm of the Cape Fold Belt. These interannual changes are mimicked by the springs, suggesting fast groundwater flow. However, steady flow rates, temperatures and limited seasonal changes in the discharge indicate slow stable flow. A layered aquifer model is therefore proposed, in which more recent recharge can travel faster in shallow zones at the same time as older groundwater travelling more slowly in deeper parts of the aquifer.

Monitoring spring discharge isotope compositions monthly, along with continued precipitation sampling, should allow a better understanding of the proposed model. Discharge rates and temperature, although harder to measure accurately, would also be useful.

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