Cl⁻と安定同位体の標識による地下水成分の同定

— タンザニアの半乾燥盆地における研究例 —

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Identification of Groundwater Components by Cl⁻ and Stable Isotope Signatures

— A Case Study in a Semi-arid Basin in Tanzania* —

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〈日本語要旨〉

タンザニアの半乾燥地域に位置するマクタポーラ盆地は、(1)山地及び丘陵地、(2)高地、及び(3)低地の3つの水文地形単位で構成される。この盆地の主要帯水層はマクタポーラ湿地の下に位置し、断層線に沿って破碎された花崗岩、及びそれを覆う砂礫からなる。この帯水層の深さは100mに及び、厚い湖成の粘土によって被圧されている。帯水層中の深部地下水の他に、おそらく宙水であると考えられる浅部地下水が高地や低地に存在する。

浅部地下水は広い範囲の化学及び同位体組成を示す。浅部地下水の同位体組成はおおむね local meteoric water line の下に分布し、このことは蒸発による濃縮を示す。深部地下水の組成は狭い範囲に限られており Cl⁻ 及び安定同位体の標識によって Type-1, 2 及び 3 の3つのタイプの地下水が定義される。これらの標識及びそれぞれのタイプの地下水の盆地内での分布から、Type-1は盆地北部に由来する成分であり、これに対しType-3は湿地の周りの高地で涵養された成分であるという見方ができる。Type-2は湿地の北西縁に発達する扇状地で涵養された成分であるか、あるいはType-1とType-3がほぼ半分ずつの割合で混ざり合った水であると考えられる。

Abstract

The Makutapora Basin located in a semi-arid region of Tanzania consists of three hydrogeomorphological units: 1) mountains and hills; 2) uplands; and 3) lowlands. The main aquifer of the basin is

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located underneath the Makutapora Swamp, consisting of fractured granite along fault zones, and overlying sand and gravel. The aquifer is up to 100m deep and confined by thick lacustrine clays. In addition to the deep groundwater in the main aquifer, shallow groundwater (presumably perched) is found in sandy surface deposits in the uplands and lowlands.

Shallow groundwater shows wide ranges of chemical and isotopic compositions. Isotopic composition of most shallow groundwater falls below the local meteoric water line, indicating evaporative enrichment. Deep groundwater shows narrow ranges of compositions that define Cl^- and isotopic signatures for three types of groundwater, Type-1, 2 and 3. Based on the signatures and distribution of each type of groundwater in the basin, we propose that Type-1 water is a component from the northern part of the basin, while Type-3 water is a component recharged on the uplands surrounding the swamp. Type-2 water may be a component recharged on the alluvial fans developing at the north-western margin of the swamp, or may be a half-half mixture of Type-1 and Type-3 waters.

Key words: Groundwater, Tanzania, stable isotope, chloride, deuterium, oxygen-18

1. Introduction

Understanding the origin of groundwater is an important step in the development of groundwater basins. A groundwater basin is recharged by one or several sources, each providing a component of groundwater. In some cases the existence of several different components can be inferred from a piezometric surface map, however it is not always possible to identify them on the map due to complicated hydrogeological characteristics of the basin. Even if the components are identified, estimation of the relative recharge contribution of each component to the groundwater reservoir is a difficult task because reliable information about physical parameters such as hydraulic conductivity and storage coefficient is limited.

When a component of groundwater has a unique physical or chemical property that differentiates it from others, we will call this property a "signature" of the component. Such a signature may provide a powerful tool for identification of groundwater components, and under certain restricted conditions we can estimate the relative recharge contribution of each component. Ratios of stable isotopes ($^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$) give ideal signatures due to the conservative nature of these isotopes (Gat, 1981). It is generally accepted that Cl^- also behaves conserva-

tively (Feth, 1981). Combination of two or more signatures give more confidence to the interpretation of groundwater compositions. A case study in a semi-arid basin in Tanzania that uses stable isotope and Cl^- signatures is presented in this paper to demonstrate the usefulness of such signatures in a developing area.

2. Hydrogeological Setting of the Study Area

The field site for the case study is the Makutapora Basin in central Tanzania, approximately 25km north of the nation's capital Dodoma (Fig. 1). The Makutapora basin is the main source of municipal and industrial water supply for Dodoma (Shindo *et al.*, 1986). Pumping was started in the early 1950's with a few production wells, and since then a number of observation and production wells have been drilled down to about 100m depth in and around the basin (Figs. 1 and 2). A joint research project on the recharge mechanism of the Makutapora Basin between the Tanzanian Ministry of Water and the Japanese Ministry of Education started in 1988. The following is a brief description of the climate, geology and topography of the region based primarily on a series of unpublished reports on the project (Shindo, 1989, 1990 and 1991).

The climate of the study area is characterized

Fig. 1 The Makutapora Basin and its surroundings (modified after Shindo, 1990). The Makutapora Swamp is shown as a stippled area. Solid circles represent the location of deep wells and open circles represent the location of shallow wells and a spring. The numbers match with the ones given in Table 1. Open squares represent the location of rain sampling stations. The elevation is given as meter above mean sea level.

Fig. 2 The location of deep wells in the Makutapora Swamp. Solid circles represent the location of deep wells. The numbers match with the ones given in Table 1.

by high air temperature and distinct wet and dry seasons. Average annual precipitation in Dodoma is about 560mm (Shindo, 1989), most of which occurs in the wet season from December to April. Annual mean air temperature in Dodoma is 23°C (Hayashi, 1990) and average annual Class-A pan evaporation in Dodoma is 2460mm (Shindo, 1990). Typical vegetation of the area is acacia thorn-shrub, Baobab trees, and some species of euphorbia.

The area around Makutapora is underlain mainly by granites of the Dodoma System, including pink granite, foliated and non-foliated biotite rich granite, and porphyritic granite (Ministry of Water, Energy and Minerals, 1976). The granitic rocks are believed to be of late pre-Cambrian age (Wade and Oates, 1938). In most areas the basement rocks are covered by weathering products and sediments of Neogene

age (Julian *et al.*, 1962), outcropping only at the topographical highs and along the channels of ephemeral streams. A system of NE-SW trending faults (Julian *et al.*, 1962) occurs in the area (Fig. 3). Major lowlands in the area are formed along those faults, such as the Makutapora Swamp shown as a stippled area in the center of Fig. 1. The Makutapora Basin is defined in this paper as the catchment basin of the swamp. The basin is not closed and it drains to the Hombolo Basin through an ephemeral stream, the Little Kinyasungwe River (Fig. 1).

Shindo (1990 and 1991) classified the Makutapora Basin into three principal hydrogeomorphological units; 1) mountains and hills, 2) uplands, and 3) lowlands, whose areas of extent are shown in Fig. 3. The mountains and hills unit includes the

Fig. 3 Hydrogeomorphological classification map of the Makutapora Basin (after Shindo, 1991)

Chenene Hills and many isolated small hills. The uplands unit represents a slightly uplifted, low-relief terrain bounded by slopes from the lowlands. Fundamentally they are pediplains that include pediplain upland, upland slope, and pediment. A pediplain is an erosional surface formed through a long-term process of pedimentation (Shindo, 1990). The lowlands unit consists of fluvial lowland, alluvial fan, and swamp. Shindo (1991) noted that pediplain uplands, fluvial lowlands, and alluvial fans (briefly described below) had high potential for groundwater recharge.

White sandy soil of the pediplain uplands is generally 1-5m thick. Shindo (1991) reported the infiltration capacity (measured using a double ring infiltrometer) as 88.5mm/hr at the observation site about 4km west of the Makutapora pumping station. In the fluvial lowlands, the depth to the bedrock surface varies from several meters to 60m near Kitope, where the Ministry of Water, Energy and Minerals (1976) reported the presence of a buried river channel. Shindo (1991) reported high infiltration capacity (65.7-81.5mm/hr) of the sandy soil of the fluvial lowland near Mtungutu. Alluvial fans develop at the foot of the Mlemu Fault and the Mundemu Fault. Shindo (1991) suggested the possibility of groundwater recharge based on the observations that runoff was small on the fans and that river water infiltrated into the fans.

The main aquifer of the Makutapora Basin consists of 1) sand and gravel, 2) weathered granite, and 3) fractured granite (Ministry of Water, Energy and Minerals, 1976). Borehole drilling by the Ministry of Water, Energy and Minerals showed that in the Makutapora Swamp granites are fractured and weathered along the Mlemu and Kitope Faults, and are overlain by up to 40m thick sand and gravel (Shindo, 1989, Fig. 3. 2.). The sand and gravel are overlain by 10-40m thick calcretes and then by up to 50m thick clays that provide a confining layer for the aquifer. The main confined zones are generally met at a depth of about 160ft (49.76m) and piezometric levels rise 62ft (18.89m) to 65ft (19.81m) below ground level (Ministry of Water,

Energy and Minerals, 1976). Most production and observation wells are completed in this main aquifer along the faults. A few wells are cased down to calcretes and screened in sand and gravel, weathered granite, and fractured granite, while most wells are cased down to sand and gravel and open in weathered and fractured granite (Ministry of Water, Energy and Minerals, 1976). Such open holes resulted in caving and reduced yield (Shindo, 1989). We will not treat each unit as a separate aquifer in this paper since the construction of the wells does not allow us to obtain information about each separate unit. The transmissivity of the main aquifer obtained by pumping tests is in the order of 10^{-3} to 10^{-2} m²/sec (Shindo, 1989).

Currently the aquifer is pumped at the rate of 23000m³/day, and the piezometric surface is 25 to 30m below the ground surface. The piezometric heads were measured in 21 wells in the Makutapora Swamp just before the onset of the wet season in 1988; the contours (meters above mean sea level) of the piezometric surface are shown in Fig. 4.

Fig. 4 shows the groundwater flow from the northern part of the basin to the Makutapora swamp. This flow seems to occur through the fractured zone along the Kitope fault or through fluvial sediments deposited in the old channels of the Little Kinyasungwe River. Since the elevation of the swamp is 30 to 60 meters lower than the surrounding uplands, it is expected that the main aquifer underneath the swamp collects water from the uplands. The main aquifer discharges to the Hombolo Basin, north-east of the Makutapora Swamp.

Several types of shallow groundwater were recognized in the area. The most common groundwater type was found in shallow wells, typically 2 to 10m deep, that were hand-dug in the surface deposits on the pediplain uplands, fluvial lowlands, and alluvial fans (Sindo, 1990 and 1991). The Ministry of Water, Energy and Minerals (1976) reported such wells in the Kitope area as perched groundwater wells. Another groundwater type was found in the wells hand-dug in the sandy deposits of ephemeral stream beds. Since the boreholes encountered water at

Fig. 4 Piezometric surface contours of the major aquifer in the Makutapora Swamp and Cl^- concentration in the deep wells. (modified after Shindo, 1990). Piezometric head contours are in meters above mean sea level. The heads were measured in December, 1988. Cl^- concentrations are in mg / L. Open circles represent Type-1 water. Solid circles represent Type-2 water. A solid triangle represents Type-3 water.

depths greater than 50m during the drilling (Ministry of Water, Energy and Minerals, 1976), it is believed that shallow groundwater is perched in the surface deposits.

3. Methods of Sampling and Analyses

Rain water and groundwater were collected and analyzed for major ions, deuterium (D), oxygen-18 (^{18}O). Most rain water samples were collected at

the Makutapora pumping station by simply using a plastic vessel. Some rain water samples from remote locations were collected using a rainfall collector similar to the one described by Cortes and Farvol-den (1989). In the rainfall collector, 5 to 10mm of liquid paraffin was added in the collection bottle to prevent evaporation from the sample.

Shallow groundwater was sampled from hand-dug wells either by hand-pumping or by direct sampling from water surface. Deep groundwater from

the main aquifer was sampled by three different methods. Samples from production wells were collected from the tap attached to the pipe line. Most samples from non-production wells were collected by sending a steel vessel down a hole. The intake of the vessel was open when it reached the sampling depth, and a steel messenger was sent down to close the intake. In addition, some samples from non-production wells were collected by pumping when pumping tests were conducted on those wells.

Water samples were kept in polyethylene bottles until the analyses were done. The sample bottles were kept at room temperature for a few weeks to several months before they were sent to Japan where they were refrigerated. Major ions were analyzed within several weeks after arrival of the samples in Japan. Isotopic analyses of most samples were done within several months after arrival, however some were stored up to one year.

The pH was measured in the field, while alkalinity was measured in the laboratory by sulfuric acid titration. Concentrations of calcium, magnesium, sodium, and potassium were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES), whereas concentrations of chloride, sulfate, and nitrate ions were analyzed by ion exchange chromatography (IC). For most samples, the D/H ratio was measured using a mass spectrometer with zinc reduction technique (Friedman, 1953), while some samples were analyzed with uranium metal reduction technique (Bigeleisen *et al.*, 1952). $^{18}\text{O}/^{16}\text{O}$ ratio was measured by mass spectrometer with standard $\text{CO}_2\text{-H}_2\text{O}$ equilibration technique (Epstein and Mayeda, 1953).

Accuracy of ICP-AES and IC analysis are generally within 5% of concentration. Accuracy of D/H and $^{18}\text{O}/^{16}\text{O}$ analyses are 1‰ and 0.1‰ respectively when expressed as δ -value with respect to SMOW.

$$\delta = \frac{R_{\text{sample}} - R_{\text{SMOW}}}{R_{\text{SMOW}}} \times 1000$$

R_{sample} : Atomic ratio of the heavier to the lighter isotope in the sample

R_{SMOW} : Atomic ratio of the heavier to the lighter isotope in SMOW

4. Results of Chemical and Isotopic Analyses

Major ion concentrations and stable isotope ratios of groundwater samples are listed in Table 1, (originally reported by Shindo, 1990). Shindo listed several samples taken at different times for BH97/70, 118/75, and 119/75, of which Table 1 shows one sample for each well since compositional variation was small. He also listed several samples from BH88/75, of which the deepest sample (94m) that was least susceptible to contamination represented the well. The sample from BH163/75 was not included in Table 1, because contamination of this well by surface water was suspected. A well referred to as BH10/72 by Shindo (1990) is currently referred to as BH10/71 (Shindo, 1991). Several samples were taken at different times from two shallow wells (Chihanga and Mundemu), which showed significant compositional variation. Two data sets for each of those wells are included in Table 1 to show the magnitude of the variation.

In this chapter we will focus attention on chloride ion (Cl^-), deuterium (δD), and oxygen-18 ($\delta^{18}\text{O}$). As already mentioned, shallow groundwater occurs in sandy surface deposits typically at the depth of several meters, whereas deep groundwater occurs in bedrock aquifers typically at depths of 50–100m.

Distribution of Cl^- concentration in deep groundwater in the Makutapora Swamp is shown in Fig. 4, in which contours of the piezometric surface in the aquifer in 1988 are depicted. Two different ranges of concentration can be seen from Fig. 4, defining two types of groundwater: Type-1 ranges between 40 and 60mg/L and averages about 55mg/L, while Type-2 ranges between 80 and 120mg/L and averages about 90mg/L. It is noted that the two groundwaters distribute separately in the swamp; Type-1 water occurs in the northern edge of the swamp where the groundwater derived from the northern part of the basin enters the swamp as infer-

Table 1 Major ions chemistry and isotopic ratio of groundwater samples (extracted from Shindo, 1990)

Loc # match with the numbers shown in Figs. 1 and 2. Samples 1-19 are deep groundwaters taken from bedrock wells, while samples 20-31 are shallow groundwaters taken from hand-dug wells (20-24, 26-30) and a spring (25). ND means the species was not detected. NA means the species was not analyzed. Methods of sampling are as follows: P (pumping), WS (water sampler, sampling depth is noted), HP (hand-pumping), and D (direct sampling from shallow wells). Alkalinity is expressed as HCO_3^- .

Loc #	Well - ID	Date d/m/y	Method	Temp (°C)	pH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	Alk (mg/L)	SO ₄ (mg/L)	NO ₃ (mg/L)	deD (‰)	de ¹⁸ O (‰)
1	BH170/75	20/12/88	P	29.2	8.16	33.4	23.4	94.4	8.1	48.9	372	48.4	ND	-30.8	-5.49
2	BH169/75	26/11/88	P	NA	8.45	16.0	25.9	112	7.7	58.3	309	60.2	ND	-29.5	-5.37
3	BH88/75	23/11/89	WS (40m)	26.2	8.60	19.0	9.3	47.1	8.2	26.6	171	19.8	ND	-26.5	-4.90
3	BH88/75	23/11/88	WS (94m)	26.1	7.81	49.7	17.5	89.3	10.9	54.9	356	45.3	2.7	-27.3	-5.27
4	BH193/75	21/11/89	WS (65m)	27.8	7.65	61.3	25.0	109	7.0	50.8	434	53.5	ND	-29.3	-5.49
5	BH97/75	20/12/88	WS (40m)	27.0	7.93	32.3	19.2	74.5	5.9	43.5	331	39.1	ND	-24.4	-4.69
6	BH123/75	21/11/89	WS (25m)	26.3	8.26	31.0	17.4	99.4	8.6	62.3	318	12.8	3.4	-28.5	-5.27
7	BH131/75	16/02/89	P	28.5	7.38	52.7	25.3	92.1	14.8	83.9	326	64.5	11.9	-26.2	-5.02
8	BH97/70	20/11/89	P	27.6	7.35	55.6	24.6	110	6.5	80.2	372	68.9	13.0	-26.0	-4.97
9	BH117/75	21/11/89	P	28.1	7.63	58.0	25.0	104	6.6	81.7	344	69.2	13.9	-26.6	-5.03
10	BH8/54	21/11/89	P	28.5	7.45	67.1	30.1	118	7.6	118	358	77.0	25.5	-27.9	-4.87
11	BH86/78	23/11/88	WS (60m)	28.3	7.82	39.3	23.0	124	10.8	105	362	52.0	ND	NA	NA
12	BH225/74	23/11/89	P	NA	7.58	24.3	55.3	94.9	6.6	72.8	328	79.7	3.6	-27.2	-4.94
13	BH35/53	24/11/88	WS (40m)	27.8	7.40	47.2	19.9	101	7.8	77.7	349	42.7	ND	NA	NA
14	BH182/75	26/12/88	WS (40m)	26.7	8.14	34.8	24.0	93.5	5.5	77.8	NA	40.3	ND	-27.4	-4.84
15	BH118/75	20/11/89	P	29.1	7.41	58.2	26.8	92.5	6.7	84.9	296	81.5	17.0	-28.3	-4.92
16	BH119/75	20/11/89	P	28.3	7.47	58.5	26.9	95.5	7.0	84.9	295	81.3	17.0	-26.4	-4.85
17	BH26/79	30/03/89	P	NA	NA	57.2	24.8	96.5	7.0	82.3	294	80.1	20.2	-27.7	-4.90
18	BH77/87	23/11/89	P	NA	7.25	74.6	37.3	83	8.6	123	300	52.8	65.5	-22.3	-4.48
19	BH10/71	22/11/89	P	NA	7.78	57.6	20.8	98.2	6.2	54.5	381	54.4	10.3	-29.7	-5.50
20	Meia Meia/1	12/12/88	D	26.0	6.24	1.5	0.6	20.9	2.2	13.0	NA	4.8	4.5	-19.8	-3.66
21	Mtungutu	03/11/89	D	25.7	NA	ND	ND	17.0	10.5	20.1	9.3	2.0	ND	-18.1	-4.14
22	Gawaye/1	22/11/89	D	26.0	7.34	21.5	7.6	122	25.8	81.0	167	58.2	83.7	-12.8	-3.25
23	Gawaye/2	22/11/89	D	25.1	7.53	72.6	7.5	58.2	5.0	48.8	202	35.0	134	-16.9	-3.78
24	H.Makulu/2	22/11/89	D	25.6	7.02	10.1	3.4	38.2	0.68	24.4	89.3	3.2	0.24	-20.0	-4.25
25	Hombolo S.	22/11/89	Spring	NA	7.32	78.5	29.0	32.2	10.7	43.4	346	38.2	ND	-24.3	-4.88
26	Chihanga	21/12/88	HP	27.6	6.20	7.2	2.4	49.4	10.1	41.2	40.3	24.4	40.6	-15.9	-3.22
26	Chihanga	27/02/90	HP	25.0	6.27	8.3	2.5	41.5	10.0	26.1	56.1	24.1	21.6	-21.2	-4.08
27	Lugala	07/11/89	HP	26.4	NA	25.5	12.3	45.7	14.0	79.4	0	3.9	133	-21.4	-4.11
28	Mbalawala/2	04/11/89	D	26.8	NA	4.4	2.3	37.0	9.0	34.9	9.8	13.7	30.5	-26.8	-5.05
29	Riv.Nzuga	26/11/89	D	23.4	6.94	2.9	1.8	16.4	8.7	8.3	84.4	2.7	0.53	-8.7	-2.42
30	Mundemu	09/02/89	HP	26.9	6.22	21.4	8.5	76.0	8.7	73.4	44.4	21.0	128	-17.3	-3.90
30	Mundemu	26/02/90	HP	27.0	5.89	21.5	9.1	70.1	8.4	91.5	32.2	20.8	76.8	-24.9	-4.64

red from piezometric surface contours, while Type-2 water occurs in the central to south-western portion of the swamp.

In addition to the wells in the swamp, a deep well located on the upland, south of the swamp (BH77/87), and another deep well at Meia Meia (BH10/71) were sampled. The Cl^- concentration of BH77/87 is 123mg/L (Fig. 4), which is higher than the range of Type-2 water. Although only one sample was obtained, we will define this water as Type-3. The Cl^- concentration of BH10/71 is 54.5mg/L (not shown in Fig. 4), which is in the range of

Type-1 water.

Shallow groundwater shows a wide range of Cl^- concentrations (Table 1). Large seasonal variations of the concentration were observed for shallow wells in Chihanga and Mundemu (Table 1). Cl^- concentrations of deep groundwater were generally within 5mg/L of the values in Table 1 throughout the study period (Shindo, 1990, p116-117).

The local meteoric water line (LMWL) can be employed as a useful reference framework to present the isotopic results. The concept of the meteoric water line was introduced by Craig (1961) to describe

Fig. 5 δD and $\delta^{18}O$ in precipitation. (after Shindo, 1990)

the global trends of δD and $\delta^{18}O$, while its theoretical basis was given by Dansgaard (1964). In this study, 45 rain samples from the Makutapora Basin and surrounding area were analyzed for δD and $\delta^{18}O$ to construct the LMWL for the basin. The results are plotted in Fig. 5. The least squares fit that defines LMWL is given by:

$$\delta D = 8.19 \delta^{18}O + 15.3$$

The arithmetic means of δD and $\delta^{18}O$ for 45 samples are -20.7‰ and -4.40‰ , respectively, which give the best available estimate of the average isotopic composition of the precipitation.

Variations of $\delta^{18}O$ values in 1988-1989 and 1989-1990 wet seasons are shown in Fig. 6, while daily rainfall in 1989-1990 wet season is shown in Fig. 7. It is clear from these diagrams that rains in the late wet season were not collected, therefore the arithmetic mean may be biased compared to the true average precipitation. It appears from Fig. 6 that the pattern of the seasonal variation is consistent in two

wet seasons. Altitude of sampling stations at Meia Meia, Mkondai, and Chenene are about 50, 120, and 230m, respectively higher than the Makutapora station. Variations of $\delta^{18}O$ values due to altitude difference can not be seen in Fig. 6.

Groundwater δD and $\delta^{18}O$ values are shown in Fig. 8. Shallow groundwater shows a wide range of isotopic composition in comparison to deep groundwater. Each type of deep groundwater has similar isotopic composition that distinguishes it from other types, therefore each type of groundwater is identified by two signatures (stable isotopes and Cl^-). The signatures become more evident in Fig. 9 where δD is plotted against Cl^- concentration. While shallow groundwater does not show significant trend in $\delta D-Cl^-$ space, deep groundwater forms a cluster for each type, with a few exceptions.

The sample from BH97/75 has a more enriched isotopic composition than other Type-1 water samples (Fig. 8). This sample was taken from standing water (40m) in an observation well that was cased

Fig. 6 Seasonal variation of $\delta^{18}\text{O}$ in precipitation. (modified after Shindo, 1990)
The location of sampling stations are shown in Fig. 1. The samples from Makutapora were collected in both 1988-1989 and 1989-1990 wet seasons. Other samples were collected only in 1989-1990 wet season.

Fig. 7 Daily rainfall at Makutapora Pumping Station in 1989-1990 wet season.

down to the depth of 77m. Such enriched isotope composition was observed in a sample from standing water (40m) in a near by observation well BH88/75 that was cased down to the depth of 57m. These samples deviate from other Type-1 water samples in Fig. 9, while the sample of BH88/75 taken from the depth of 94m does fall in Type-1 composition. It is suspected that the isotopic composition of the sample from BH97/75 deviates from that of water in the aquifer, probably due to contamination by surface

water or other unknown sources. The sample from BH8/54 has higher Cl^- concentration than other Type-2 water samples. The reason for the high concentration is unknown at present.

5. Discussion

(1) Enriched isotopic composition of shallow groundwater

Shallow groundwater shows a wide range of

Fig. 8 δD and $\delta^{18}O$ in groundwater.

LMWL denotes the local meteoric water line given by the equation shown in Fig. 5. Shallow GW stands for shallow groundwater.

Fig. 9 Correlation between Cl^- concentration and δD in groundwater.

Note that the sample from BH97/75 and the shallow (40m) sample from BH88/75 deviate from other Type-1 waters, and the sample from BH8/54 deviates from other Type-2 waters.

isotopic composition (Fig. 8), most of which falls below the local meteoric water line (LMWL). It is well known that the isotopic composition of soil water undergoing evaporation follows a slope much lower

than 8 in δD - $\delta^{18}O$ space (Allison, 1982). Shallow groundwater, thus, appears to be subjected to evaporative enrichment. The degree of enrichment varies between wells reflecting the wide variety of

settings, such as soil types, depth to water table, and well construction. Perched shallow groundwater is expected to undergo strong enrichment.

(2) Origin of deep groundwater

Despite the large variation of isotopic composition in rain water (Fig. 5), deep groundwater shows little variation (Fig. 8). Fluctuation of isotopic composition of rain water is dissipated completely in the recharge processes, thus in many cases the composition of meteoric groundwater is found to match the mean composition of precipitation over the recharge area to a fair approximation (Gat, 1981).

The deep groundwater from BH10/71 has Cl^- concentration, δD , and $\delta^{18}\text{O}$ values that fall within the range of Type-1 water, which indicates that BH10/71 and Type-1 water have the same identity. Based on this and the piezometric surface map (Fig. 4), we propose that the origin of Type-1 water is the groundwater derived from the northern part of the basin where BH10/71 is located.

Type-1 water has depleted isotopic composition compared to Type-2 and Type-3 waters. One possible explanation for the depleted composition is the altitude effect (Yurtsever and Gat, 1981). Altitude of the northern part of the basin is higher than the southern part, thus the groundwater recharged in the northern part may have depleted isotopic composition. Fig. 6, however, does not show any effect of altitude in precipitation. It will be necessary to carry out more comprehensive rain sampling to see if the altitude effect is significant in the Makutapora Basin.

Type-2 water is distributed in the central to south-western portion of the swamp (Fig. 4). We believe that the composition of Type-2 water is more close to that of the local recharge around the swamp than that of Type-1 water. Two hypotheses regarding the origin of Type-2 water are presented below to guide future studies.

The first hypothesis assumes direct recharge of Type-2 water around the swamp. Shindo (person. comm., 1993) recently found that large recharge was taking place on the alluvial fans at the foot of the

Mlemu Fault, which may be the origin of Type-2 water. A problem with this hypothesis is the difference of isotopic composition between the average precipitation and Type-2 water (Fig. 8). As mentioned earlier, the average precipitation calculated from the 45 samples collected in this study (shown in Fig. 8) may be biased due to incomplete coverage of an entire wet season. The true average composition of precipitation must be determined to examine the validity of the hypothesis.

In the second hypothesis, the origin of Type-2 water is explained by the mixing of Type-1 and Type-3 waters. Fig. 9 shows that the composition of Type-2 water falls between Type-1 and Type-3 water. When two components of water are mixed, concentrations of conservative species show a linear correlation. Conservative behaviors of the stable isotopes and Cl^- will be discussed in the next paragraph.

From Fig. 8, there is very little doubt that the groundwaters in the Makutapora Basin are of meteoric origin, and thus δD and $\delta^{18}\text{O}$ behave conservatively. Common Cl^- sources are input from precipitation, dissolution of halite, mixing with present sea water or connate water, and leaching from marine sediments. The last two are not likely in the Makutapora Basin, while the precipitation input does not affect the mixing process in aquifers. Halite deposits are not reported in the Makutapora Basin, although it may be possible that calcrete layers above the aquifer contain Cl^- . Ministry of Water, Energy, and Minerals (1976, p14) analyzed a calcrete sample from BH182/75, and showed that it consisted of 85.4% as CaCO_3 , and the rest (acid insolubles) mainly of quartz grains with some mica. While more information is desired, we assume that Cl^- is not a major component of calcretes, thus it behaves conservatively in the aquifer.

Based on the assumption that Cl^- , δD , and $\delta^{18}\text{O}$ behave conservatively, we can interpret the composition of Type-2 water shown in Fig. 9 as the mixing of Type-1 and Type-3 waters. We propose that Type-3 water represents the deep groundwater recharged on the uplands surrounding the Makuta-

Fig.10 Correlation between Cl^- concentration and $\delta^{18}\text{O}$ in deep groundwater.
The linear correlation between two species indicates the mixing of Type-1 and Type-3 waters.

pura swamp, based on the location of BH77/87. Type-3 water has the isotopic composition close to calculated average precipitation (Fig. 8). Type-2 water, therefore, is proposed to be a mixture of the components from the northern part of the basin (Type-1) and the uplands around the swamp (Type-3). Fig. 10 plots $\delta^{18}\text{O}$ against Cl^- concentration for deep groundwaters, which shows the same mixing trend as shown in Fig. 9. The mixing ratio of Type-1 and Type-3 read from Fig. 10 is approximately half-half.

To understand the origin of Type-2 water, it will be necessary to determine the average isotopic composition of precipitation, and to collect more samples of Type-3 water.

6. Conclusions

Chemical and isotopic compositions of groundwater and rain water in the Makutapora Basin were studied in this paper to identify groundwater components. The local meteoric water line (LMWL) in the basin based on 45 rain samples is given by:

$$\delta^{18}\text{D} = 8.19 \delta^{18}\text{O} + 15.3$$

Isotopic composition in precipitation showed a consistent seasonal pattern in two wet seasons studied. The altitude effect was not evident from the analysis of a small number of samples.

In the Makutapora Basin, shallow groundwater occurs in sandy surface deposits at a depth of several meters, whereas deep groundwater occurs typically 50-100m deep in the bedrock and sand and gravel. Shallow groundwater shows wide ranges of chemical and isotopic compositions. Isotopic compositions of most shallow groundwater fall below LMWL, indicating evaporative enrichment. Deep groundwater, in contrast, has a narrow range of compositions.

Three types of deep groundwater are identified by signatures characterized by Cl^- concentration and δD and $\delta^{18}\text{O}$ values. We propose that Type-1 water is a component from the northern part of the basin, while Type-3 water represents a component recharged on the uplands surrounding the Makutapora Swamp. Two hypotheses are proposed regarding the origin of Type-2 water. The first hypothesis considers Type-2 water as being recharged locally around the swamp, possibly on the alluvial fans at

the foot of the Mlemu Fault. In the second hypothesis, Type -2 water is considered to be a mixture of Type-1 and Type-3 waters, based on the linear relation between Cl^- concentration and $\delta^{18}\text{O}$ of the deep groundwaters. The mixing ratio is estimated to be half-half.

The average isotopic composition of precipitation is an important piece of information in studying the origin of Type-2 water. The rain samples collected in this study did not cover an entire wet season, thus the average composition calculated from those samples may be biased. More comprehensive rain sampling is recommended to determine the true average composition, as well as to examine the significance of the altitude effect.

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