Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25506

جمعية علوم وتقنية المياه
Water Sciences and Technology Association

Connectivity between aquifers: evidence from $^{87}Sr/^{86}Sr$ ratio and from stable isotopes case study of Oman

Khadija Semhi[a], Osman Abdalla[a], Talal Al Hosni[a], Rashid Al Abri[b]

[a]*Department of Earth Sciences, College of Science, Sultan Qaboos University, P.O. Box: 36, Alkhode 123, Muscat, Sultanate of Oman*
[b]*Ministry of Regional Municipalities and Water Resources, Muscat, Sultanate of Oman*

ABSTRACT

Isotope techniques are powerful tools in hydrological studies such as determination of groundwater age, recharge source, groundwater mixing etc. The aim of this study is to identify physico-chemical processes that control groundwater in North Oman. We have collected several groundwater samples in North Oman from different geological units namely the tertiary formations, Hajar super group (HSG) formations and ophiolite which comprise different aquifers. All groundwater samples were analyzed for strontium $^{87}Sr/^{86}Sr$ ratio and environmentally stable isotopes ($^{18}O/^{16}O$ ($\delta^{18}O$) and $^{2}H/^{1}H$ ($\delta^{2}H$)). The analysis of the stable isotopes data ($\delta^{2}H$ and $\delta^{18}O$) suggests (1) a groundwater recharge to the ophiolite from the HSG and from direct infiltration and (2) groundwater in the tertiary formations formed from meteoric and evaporated waters. The different aquifers have shown variable $^{87}Sr/^{86}Sr$ ratio that ranges between 0.70840 and 0.70864 for the ophiolite aquifer, 0.70776 and 0.71141 for groundwater from the Tertiary aquifer and from 0.70798 to 0.70938 for the groundwater from the HSG aquifer. The relationship between $^{87}Sr/^{86}Sr$ ratio and 1/Sr indicates aquifers' inter-connectivity and suggests recharge from the HSG into the ophiolite. Groundwater of the Tertiary aquifer is from two main reservoirs: (1) a reservoir generated by a mixture of groundwater from the ophiolite and HSG aquifers and (2) a reservoir generated by a direct infiltration of rainwater and its interaction with evaporites.

Keywords: Isotopes; Mixing; Recharge; Strontium; Aquifer

1. Introduction

The renewability of groundwater, which comprises the main water resources in arid areas, is vital for development plans and sustainability. Increasing water demand has greatly stressed the water resources causing resources depletion, deterioration of water quality and aquifer hydraulic properties and encourages seawater intrusion in coastal areas.

Isotopes are found to be very powerful tools to investigate aquifer interrelations, surface water and groundwater interactions and infiltration through the soil zone. In previous studies, hydrological investigations of groundwater in Oman using isotopes revealed mixing and interactions between deep and shallow waters (McCarthy et al., 1992; Horst et al., 2007; Nakaya et al., 2007; Makni et al., 2013) but did not distinguish those between different types of aquifers. Among isotopes, ^{18}O and ^{2}H are the most commonly used to determine such hydrological information including the sources of recharge and groundwater mixing.

The D/H and $^{18}O/^{16}O$ ratios in precipitations vary according to elevation and distance from the ocean. The D/H and $^{18}O/^{16}O$ ratios in water may also sometimes change within the aquifer due to evaporation and exchange and mixing processes between waters and interaction with rocks. Such approaches are commonly used for hydrological purposes (Yeh et al., 2009, Saka et al., 2013).

Although the application of stable isotopes in hydrological studies has been carried out intensively, most of these studies were focusing on individual aquifers and rarely consider geological diversity (Davisson et al., 1999; Petrella and Celico, 2013; Saka et al., 2013; Swarzenski et al., 2013).

In the current study, we are using D and ^{18}O and strontium isotopes to investigate the hydrogeology of terrains

Presented at the 13th Gulf Water Conference – Water in the GCC: Challenges and Innovative Solutions. 12–14 March 2019, Kuwait

1944-3994/1944-3986 © 2020 Desalination Publications. All rights reserved.

characterized by diversified geology. The better understanding of such hydrogeology is necessary for well informed management plans and future development. The water sustainability management is highly dependent on mapping the pathways of groundwater in each aquifer and identifying the mixing processes.

This study is carried in order to (1) characterize the isotopic composition of groundwater from North Oman and investigate the evaporation effect and (2) investigate the connectivity between groundwater from different aquifers.

1.1. Study area

The study area covers a total geographical area of about 82,259 km^2 (Fig. 1). It is bounded by Oman Sea from the North with an extending coast of about 300 km up to United Arab Emirates (UAE) border. The mean monthly temperature in the mountainous area varies between 4.6°C and 17.6°C while in the plains and coastal areas it was reported between 18.9°C and 35.7°C (Al Abri, 2009). The average rainfall calculated for North Oman is about 100 mm. The mean annual

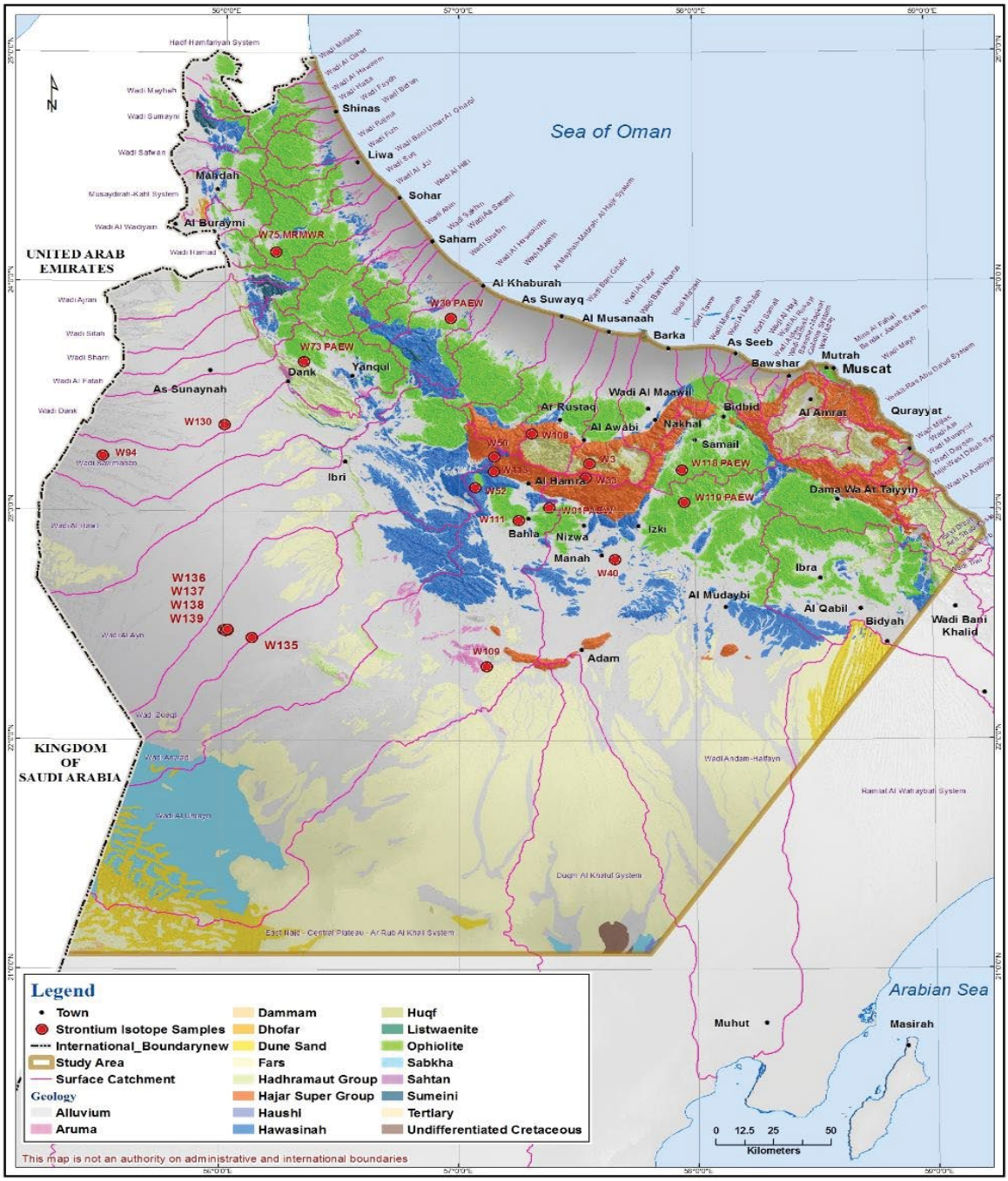

Fig. 1. Geology of Oman and sampling locations.

evaporation rates have been found to be 2,359 mm in the mountainous area (Jabal Shams station) in the summer time and drops to about 1,500 mm in winter time while it is about 2,260 mm in the plain area (MRMWR, 2006).

The study area is characterized by diversified geology that extends from Precambrian to recent. It comprises in general five main rock sequences, Hajar super group (HSG, carbonate rocks about 270–90 Ma age), Hawasina Formation (consolidated ancient seafloor sediments about 270–90 Ma age), ophiolite (igneous rocks), Tertiary (shallow marine carbonates about 65–2 Ma age) and recent alluvial deposits (Glinne, 2005; Al Abri, 2009). In the core of the Jabal Akhdar that represents the highest elevation, metamorphosed rocks of pre-Permian age are reported (Glinne, 2005).

2. Materials and methods

2.1. Sampling and analytical methods

Several samples were collected from groundwater hosted in ophiolite and limestone (Fig. 1). Samples were filtered through 0.45 μm diameter and analyzed for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ and Sr isotopes. Analysis of oxygen $^{18}O/^{16}O$ and $^{2}H/^{1}H$ for most of samples were determined in Ottawa University, faculty of science, Earth Science G.G. Hach Isotope laboratories and in Environmental Isotope Laboratory ETLAB at University of Waterloo in Canada by laser absorption spectroscopy using a Los Gatos Research (LGR) Isotopic Water Analyzer (IWA-35d-EP) Model 912-0026. Routine precision for hydrogen is +/–1 per mil. Routine precision for oxygen is +/–0.25 per mil. The results are reported with respect to International Atomic Energy Association (IAEA), international standard Vienna standard Mean Oceanic Water (VSMOW) and expressed in delta values, δ, in units of per mil relative variation with respect to VSMOW:

$$\delta = \text{Rsample} - \frac{\text{Rstandard}}{\text{Rstandard}}$$

where Rsample is the ratio of the heavy to the light isotope measured for the sample and Rstandard is the equivalent ratio for the standard.

Analysis of Sr isotopes was carried in the Ottawa University, faculty of science, Earth Science G.G. Hach Isotope laboratories and some in Environmental Isotope Laboratory ETLAB at University of Waterloo in Canada.

3. Result and discussion

3.1. Stable isotopes

For the discussion of results, groundwater samples are divided according to the type of their aquifer rocks (Table 1). The investigated groundwater is from the following aquifers: ophiolite, limestone of Hajar super group (HSG) and limestone of tertiary. The plot of δD vs. $\delta^{18}O$ is discussed relative to the Global Meteoric Water Line defined by Craig (1961) (Fig. 2), and to Northern Oman Meteoric Water Line (NOMWL; $\delta 2H = 5\delta^{18}O + 10.7$) and the Southern Oman Meteoric Water Line (SOMWL; $\delta 2H = 7.2\delta^{18}O–1.1$) suggested by Weyhenmeyer et al. (2002). The stable isotopes data ($\delta^{18}O$ and δD) have been used for investigation of interactions

Table 1
Stable and Sr isotopes in groundwater from ophiolite, Hajar super group (HSG) and tertiary aquifers

	Ophiolite					HSG					Tertiary			
	Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD		Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD		Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD
	mg/L		(per mil SMOW)			mg/L		(per mil SMOW)			mg/L		(per mil SMOW)	
W19 PAEW	0.27	0.70844	–1.55	–2.05	W3 PAEW	0.74	0.70938	–3.96	–20.2	W94	6.87	0.70841	–1.62	–11.9
W73 PAEW	0.49	0.70853	1.45	2.76	W33 PAEW	0.61	0.70858	–3.90	–20.2	W130	1.22	0.70861	–1.62	–6.9
W75 MRMWR	0.01	0.70799	–1.39	–10.44	W49 PAEW	1.74	0.70846	–1.00	–6.1	W135	17.32	0.70785	–2.78	–13.67
W80 PAEW	0.57	0.70864	–0.06	–2.07	W50 PAEW	2.42	0.70837	–2.61	–14.6	W136	15.55	0.70784	–2.56	–10.61
w91PAEW	0.37	0.70863	–0.68	–4.84	W52 PAEW	0.67	0.70806	–2.48	–11.6	W137	15.86	0.70785	–2.64	–10.36
W111	0.23	0.70853	–0.64	–3.16	W108	0.67	0.70855	–2.95	–17.0	W138	85.8	0.71141	–2.11	–20.83
W118 PAEW	0.1	0.70809	0.29	0.92	w109	7.55	0.70832	–1.38	–6.6	W139	28.16	0.70776	–2.60	–13.17
Average	0.29	0.71000	–1.212	–5.63	W113	0.01	0.70798	–0.55	–1.79	Average	24.3971	0.70853	–1.63	–10.26
Min	0.01	0.70799	–4.72	–24.01	Average	1.80125	0.70846	–2.38	–11.47	Min	1.22	0.70776	–4.44	–21.33
Max	0.57	0.70864	1.45	2.76	Min	0.01	0.70798	–4.16	–20.23	Max	85.8	0.71141	–0.16	–1.79
SdV	0.19	0.00020	1.077	4.91	Max	7.55	0.70938	–0.52	–1.79					
					SdV	2.28	0.00040	1.137	5.99					

between different aquifers as well. The approach employs the relationship between $\delta^{18}O$ and δD which is used to highlight the groundwater mixing between relatively unaffected waters and those being influenced by evaporation and/or by mixing with other water sources.

The isotopic composition of groundwater from the ophiolite aquifer ranges from –24 to 2.73.0‰ V-SMOW for δD and from –4.72 to 1.45‰ V-SMOW for $\delta^{18}O$. The $\delta^{18}O$ and δD in groundwater samples is referenced to LMWLs previously defined by Weyhenmeyer et al. (2002) in addition to GMWL ($\delta D = 8\ \delta^{18}O + 10$, Craig, 1961).

Most of groundwater samples collected from the ophiolite aquifer during this study plots between NOMWL and SOMWL (Weyhenmeyer et al., 2002) and shows an evaporation effect indicated by a slope of 3.8 and intercept of –0.96 (Fig. 2).

The isotopic composition of the groundwater from HSG aquifer ranged from –20.2 to –1.79.0‰ V-SMOW for δD and from –4.16 to –0.52 ‰ V-SMOW for $\delta^{18}O$.

The δD–$\delta^{18}O$ relationship showed that most of wells plot close to GMWL with a slight deviation which defines the following regression equation: $\delta D = 5\delta^{18}O + 0.57$ (Fig. 2).

The deviation of waters of the few wells from the GMWL indicates an effect of only slight evaporation. However water of most wells plot near the SOMWL rather than near to NOMWL.

The isotopic composition of groundwater from Tertiary aquifer ranged from –21.33 to –1.79‰V-SMOW for δD and from –4.44 to 0.16‰V-SMOW for $\delta^{18}O$. The $\delta^{2}H$ – $\delta^{18}O$ relationship for all water samples showed that there are two groups of groundwater (1) those which plot on the GMWL, and (2) those which have undergone evaporation and which plot in two parallel distributions (Fig. 2).

3.2. Sr isotopes

The concentrations of Sr in groundwater collected for this study from ophiolite range from 0.1 to 0.57 mg/L much lower than that measured by Lanphere et al. (1981) in rocks from Samail ophiolite (about 87 to 278 ppm).

Although the Sr concentration in groundwater remain lower than that measured in the Samail ophiolite rocks, the $^{87}Sr/^{86}Sr$ ratio about 0.7084 to 0.7086 (Table 1) is higher than $^{87}Sr/^{86}Sr$ ratio measured in rocks from ophiolite rocks (about 0.7028 to 0.7040) by McCulloch et al. (1981) and Lanphere et al. (1981). Indeed the relationship between $^{87}Sr/^{86}Sr$ and 1/Sr is considered to identify the different sources of Sr in waters of this aquifer (Fig. 3). Although the difference between $^{87}Sr/^{86}Sr$ of different wells is not significant (about 10%), it is clear that Sr in groundwater of ophiolite aquifer is yielded from two main sources (1) one with high concentration of Sr and slightly high $^{87}Sr/^{86}Sr$ and (2) the other with low Sr concentration and slightly lower $^{87}Sr/^{86}Sr$. The source 1 may reflect meteoric waters with an effect of evaporation. The source 2 can be apparented to young waters which have interacted with limestone of HSG which were deposited during Cretaceous.

The $^{87}Sr/^{86}Sr$ ratio in waters collected from Tertiary aquifer varies from 0.70776 to 0.708612. Like waters from ophiolite, groundwater from Tertiary aquifer exhibit small variations of $^{87}Sr/^{86}Sr$ ratio and large variations in the Sr concentrations.

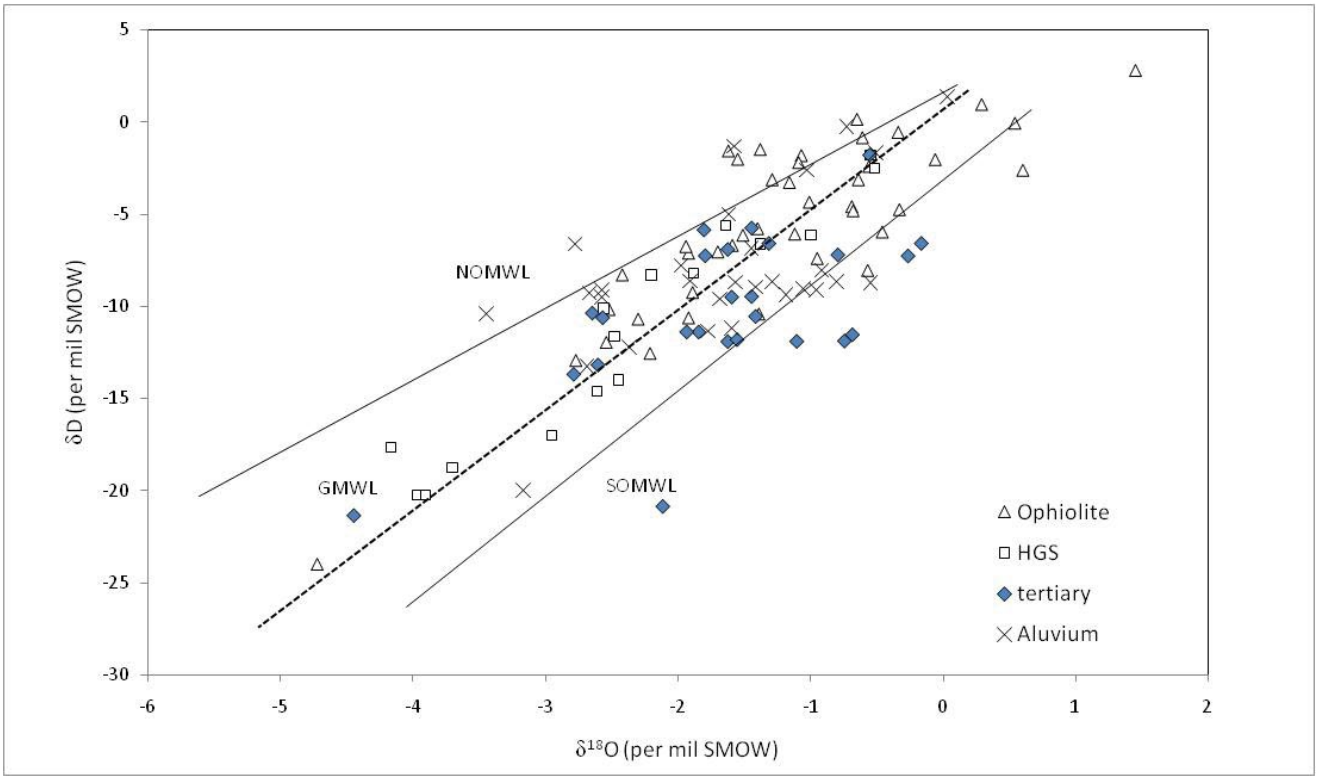

Fig. 2. δD–$\delta^{18}O$ diagram for groundwater from different aquifers.

Sr isotopes data of groundwater from Tertiary aquifer indicates two main reservoirs, (1) one with low $^{87}Sr/^{86}Sr$ and high Sr concentration and (2) one end member with slightly higher $^{87}Sr/^{86}Sr$ and low Sr concentrations (Fig. 3).

The endmember with higher concentration in Sr and lower $^{87}Sr/^{86}Sr$ ratio can correspond to evaporite rocks which have been identified in tertiary formation while the more radiogenic endmember (2) may correspond to infiltration of waters from ophiolite aquifer. These infiltrated waters are characterized by isotopic signature yielded from limestone of HSG.

The $^{87}Sr/^{86}Sr$ ratio in waters collected during this study from HSG aquifer vary from 0.70798 to 0.70858 while the Sr content is about 0.01 to 7.6 mg/L. The plot of $^{87}Sr/^{86}Sr$ vs. 1/Sr of groundwater samples collected from HSG aquifer involves mixing between at least 3 end members (Fig. 3). These various water source endmembers consist of: 1) waters with high Sr concentration and low $^{87}Sr/^{86}Sr$ (Figs. 3 and 2) waters with high $^{87}Sr/^{86}Sr$ and low concentration and 3) waters with low Sr concentrations and low $^{87}Sr/^{86}Sr$.

The endmember 1 can be related to dissolution of carbonates while endmember 2 seems to be related to silicate minerals. The endmember 3 is likely apparented to infiltrated rainwater which does not reflect neither an effect of evaporation nor an important interaction with carbonate rocks.

3.3. Connection between different aquifers

The groundwater interaction between different aquifers can be determined using the variation of δD vs. $\delta^{18}O$ and Sr isotopes.

The δD and $\delta^{18}O$ in groundwater from the HSG aquifer is more homogeneous when compared with other aquifers. The karstification in the HSG, its location in the high altitude with anomalous rainfall and less evaporation (cool climate) accelerates the percolation to the aquifer and therefore the isotopic signature remains unaffected. Groundwater moves from the HSG through fractures and faults to feed the other aquifers resulting in mixing of groundwater. This is a slower process compared with percolation to the HSG. Therefore, considerable variation of δD and $\delta^{18}O$ values characterizes groundwater from the ophiolite. Groundwater from tertiary plot between waters hosted in ophiolite and those in HSG indicating that the recharge of tertiary is a mixing between these waters (ophiolite and HSG). These mixing waters may discharge to other groundwater hosted in ophiolite aquifer, those which are enriched in $\delta^{18}O$.

Comparison between $^{87}Sr/^{86}Sr$ data of waters from all aquifers (Fig. 3) shows that the lowest $^{87}Sr/^{86}Sr$ ratio and the highest concentration of Sr characterize waters from Tertiary aquifer (deeper than wells in the other aquifers) while the lowest Sr concentration was measured in waters from ophiolite.

Although the recharge processes to each aquifer do not look similar, the sources of recharge to different aquifers seem be connected. The location of HSG samples in the center of all samples collected from the other aquifers support the suggestion of discharge of waters hosted in HSG to all aquifers. Among groundwater hosted in HSG (in the recharge zone), there are wells which plot near tertiary, and other wells plot near ophiolite.

The similarity of $^{87}Sr/^{86}Sr$ of waters in ophiolite with those hosted in HSG reflects a short residence time of waters

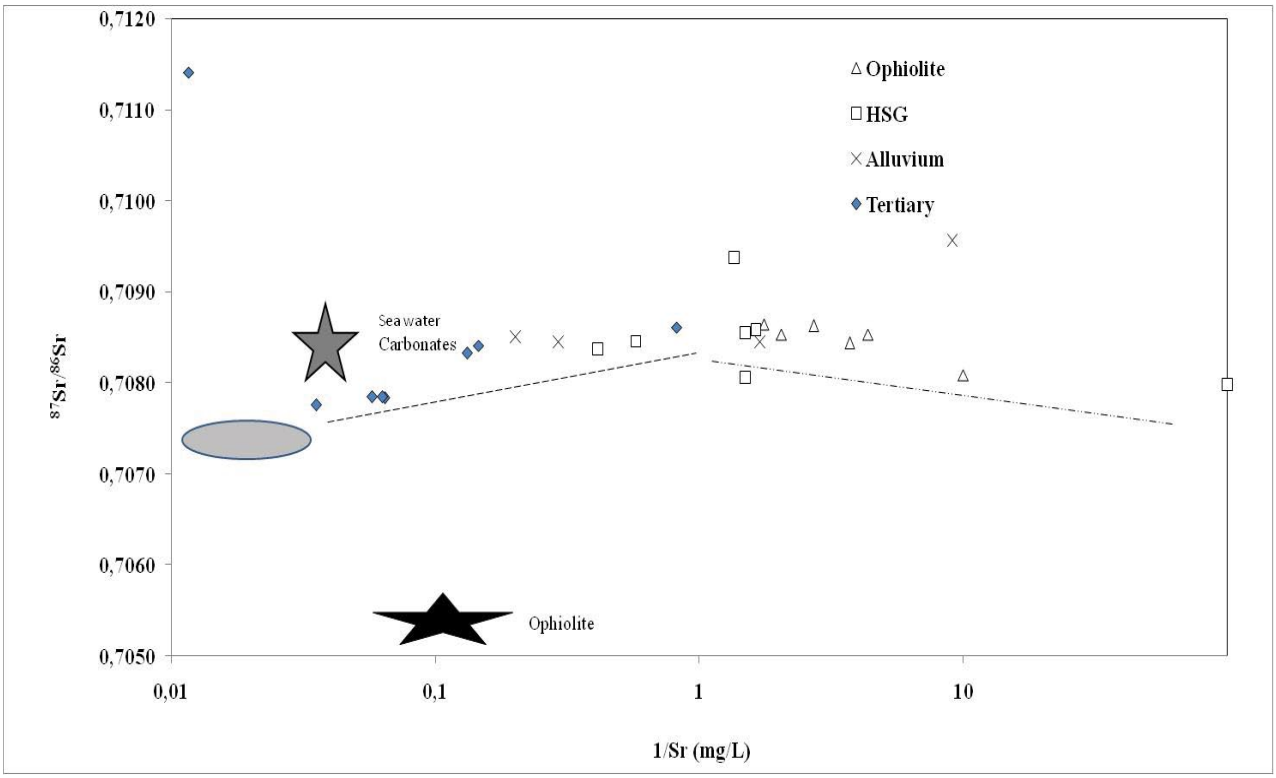

Fig. 3. Variations of $^{87}Sr/^{86}Sr$ ratio vs. 1/Sr.

in ophiolite. Moreover because of their low solubility degree, ophiolite interaction with waters does not influence the $^{87}Sr/^{86}Sr$ ratio of water. It is clear that the source of recharge to ophiolite waters consists in waters from HSG. A possible discharge of waters from ophiolite to waters in Tertiary aquifer can be an explanation of similarity of $^{87}Sr/^{86}Sr$ ratio measured in waters of ophiolite with that in waters from one endmember of Tertiary aquifer (the endmember with high $^{87}Sr/^{86}Sr$).

4. Conclusion

Based on stable isotopes:

- Waters in Tertiary aquifer are a mixture between waters from a shallow source apparented to ophiolite and a deep source apparented to HSG.

The source of groundwater and the connectivity between aquifers has also been shown using $^{87}Sr/^{86}Sr$ ratio vs. 1/Sr plot which indicates that:

- Waters from ophiolite are recharged from HSG
- The waters from Tertiary formation are recharged from two main sources: (1) waters with high $^{87}Sr/^{86}Sr$ are recharged from a possible mixture between waters from HSG and waters from ophiolite and (2) waters with low $^{87}Sr/^{86}Sr$ reflect the interaction of waters with evaporite rocks.

Acknowledgements

This research was done in the frame of the Research Program HM (SQU, Oman). The authors would like to thank sincerely the staff of Ministry of Regional Municipalities and Water Resources for their support and the staff of Isotope laboratory (Ottawa University) for all isotopic analysis.

References

Al Abri, R. 2009. Statistical and hydrochemical characterization of wadi Umairy. Sultanate of Oman, unpublished master thesis. Sultan Qaboos University, Sultanate of Oman.

Craig, H., 1961, Isotopic Variations in Meteoric Waters. Science, New Series 133 (3465): 1702–1703.

Davisson, M.L., Smith. D.K., Kenneally. J., and Rose, T.P., 1999, Isotope hydrology of southern Nevada groundwater: Stable isotopes and radiocarbon. Water Resources Research 35 (1): 279–294.

Glinne, K.W., 2005, The Geology of Oman Mountains, An outline of their origin. University of Aberdeen, UK.

Horst, A., Mahlknecht, J., Merkel, B.J., 2007, Estimating groundwater mixing and origin in an overexploited aquifer in Guanajuato, Mexico, using stable isotopes (strontium-87, carbon-13, deuterium and oxygen-18). Isotopes Environ Health Stud. 2007 Dec; 43(4): 323–38.

Lanphere, M.A., Coleman, R.G. and Hopson, C.A., 1981, Sr Isotopic Tracer Study of the Samail Ophiolite, Oman. Journal of geophysical research, 86 (B4): 2709–2720.

Makni, J., Ben Brahim, F., Hassine, S., Bouri, S. and Ben Dhia, H., 2014, "Hydrogeological and Mixing Process of Waters in Deep Aquifers in Arid Regions: South East Tunisia," Arabian Journal of Geosciences 7 (2): 799–809.

McCarthy, K.A., McFarland, W.D., Wilkinson, J.M., and White, L.D, 1992, The dynamic relationship between ground water and the Columbia River: using deuterium and oxygen-18 as tracers, J. Hydrol., 135: 1–12.

McCulloch, M.T., Gregory, R.T., Wasserburg, G.J., Taylor, H.P, 1981, Sm-Nd, Rb-Sr, and 18 O/ 16 O Isotopic Systematics in an Oceanic Crustal Section: Evidence From the Samail Ophiolite. Journal of Geophysical Research Atmospheres 86(B4): 2721–2735.

Ministry of Regional Municipalities & Environment and Water Resources. 2006, Water Resources in the Sultanate of Oman (second edition). Ministry of Regional Municipalities and Water Resources, Sultanate of Oman.

Nakaya, S., Uesugi, K., Motodate, Y., Ohmiya, I., Komiya, H., Masuda, H. and Kusakabe, M., 2007, Spatial separation of groundwater flow paths from a multi-flow system by a simple mixing model using stable isotopes of oxygen and hydrogen as natural tracers. Water Resources Research 43 (9): 1–15.

Petrella, E.E. and Fulvio, C.F, 2013, Mixing of water in a carbonate aquifer, southern Italy, analysed through stable isotope investigations. International Journal of Speleology 42 (1): 25–33.

Saka, D., Akiti, T.T., Osae, S., Appenteng, M.K and Gibrilla, A., 2013, Hydrogeochemistry and isotope studies of groundwater in the Ga West Municipal Area, Ghana. Applied Water Science 3 (3): 577–588.

Swarzenski, P.W., Baskaran, M., Rosenbauer. R.J., Edwards, B.D. and Land, M.A, 2013, Combined Radio- and Stable-Isotopic Study of a California Coastal Aquifer System. *Water 5*(2): 480–504; doi:10.3390/w5020480

Weyhenmeyer, C.E., Burns, S.J., Waber, H.N., Macumber, P.G., Matter, A., 2002, Isotope study of moisture sources, recharge areas and groundwater flowpaths within the Eastern Batinah coastal plain, Sultanate of Oman. Water Resources Research 38, 1184 doi: 10.1029/2000WR000149, 2002.

Yeh, H. Fu, Cheng, H.L, Kuo, C.H, Po, H.C and Chung, H.W., 2009, Using stable isotopes for assessing the hydrologic characteristics and sources of groundwater recharge, Journal of Environmental Engineering and Management, 19(4): 185–191.