Indo. J. Chem., 2007, 7 (1), 32 - 37

INTERPRETATION OF OXYGEN –18 ISOTOPE IN SULPHATE FROM DEEP GROUNDWATER IN JAKARTA AREA

E. Ristin Pujiindiyati*, Wandowo, and Zainal Abidin

Centre for the Application Technology of Isotopes and Radiation, National Nuclear Energy Agency
Jl. Cinere, Pasar Jumat, PO.Box 7002 JKSKL, Jakarta 12070

Received 2 January 2007; Accepted 29 January 2007

ABSTRACT

It has been done a determination of $\delta^{18}O$ (SO_4^{2-}) and $\delta^{18}O$ (H_2O) value from Jakarta deep groundwater with depth 40-140 m. The aim of this research is to know some processess influencing the composition of oxygen isotope in groundwater sulphate. A method commonly used to determine $\delta^{18}O$ (H_2O) value is according to Epstein-Mayeda. CO_2 gas resulted from equilibration process between water sample and CO_2 gas standard in which oxygen isotopic reaction has occurred, is injected to mass spectrometer. For determination of $\delta^{18}O$ (SO_4^{2-}) value, Rafter method is used. CO_2 gas released from reducing sulphate of water sample with graphite is injected to mass spectrometer. The results of $\delta^{18}O$ (H_2O) values obtained in this experiment have a narrow range from -5,04 $^0/_{00}$ to –6,65 $^0/_{00}$ SMOW whereas their $\delta^{18}O$ (SO_4^{2-}) values have a wider range from +8,3 $^0/_{00}$ to +17,4 $^0/_{00}$ SMOW. The more constant values of $\delta^{18}O$ (H_2O) performed that evaporation effects might not occur. Based on the similarity between $\delta^{18}O$ (SO_4^{2-}) values of deep groundwater and that of marine evaporite sulphate rocks, it is supposed that sulphate of Jakarta deep groundwater was derived from dissolution of this rocks. There was an indication of seawater intrusion around Pejagalan and Kamal Muara Penjaringan area based on the similarity between their $\delta^{18}O$ (SO_4^{2-}) values and $\delta^{18}O$ (SO_4^{2-}) of modern seawater. The contribution of oxygen from water in sulphide oxidation reaction ranged 0% to 12% suggesting that oxygen in deep groundwater sulphate was mainly derived from atmospheric molecular oxygen

Keywords: *oxygen isotope, sulphate, groundwater*

INTRODUCTION

Composition of oxygen-18 (^{18}O) isotope in natural sulphates can be used to trace sulphate origin in groundwater. This is based on the characteristic isotope having different ratio of isotope content of ^{18}O related to ^{16}O in each sulphate sources. The composition of δ ^{18}O value in groundwater sulphates is specific and will not change its composition during under a condition of major sulphate sources. However, the changes of δ ^{18}O value in groundwater sulphate may be able to take place if it is influenced by mixing process with other sulphate sources, for examples dissolving sulphate mineral, releasing SO_2 gas from volcanic or industrial activities or mixing by seawater. The oxygen isotope composition of sulphate may be also influenced by the oxygen isotope composition of any H_2O with which it has been in contact. Reaction such as isotope exchange, sulphate reduction, physical process (crystallization and adsorption), oxidation of sulphur compounds also can change δ ^{18}O value of groundwater sulphate. In the region having low temperature with normal pH, reaction of oxygen isotope exchange between sulphate and water is extremely slow so that the reaction can be neglected. In contrast to geothermal areas having higher temperature and more acidic pH, reaction of oxygen isotope exchange is faster [1,2].

Reduction process by certain anaerobic bacteria such as Desulfovibrio desulfuricans (mostly deposited in marine or lake sediment) is supposed to play in important role in altering oxygen isotope composition of sulphate. During sulphate reduction process to hydrogen sulphide, preferential reaction of the light isotope oxygen (^{16}O) containing ions enriches the unreacted sulphate in heavier isotope oxygen (^{18}O) or result more enriched δ ^{18}O value. This is caused by S--^{16}O bonds that are more easily broken than S--^{18}O bonds [3].

Each process above can give different trends if δ ^{18}O values of H_2O are plotted to δ ^{18}O values of SO_4^{2-}. The initial H_2O and SO_4^{2-} are assumed to have marine isotopic compositions. The δ ^{18}O of H_2O in seawater is supposed as a standard of 0 $^0/_{00}$ point whereas the δ ^{18}O of SO_4^{2-} in modern seawater has a very homogeneous and well defined isotopic composition of 9.5 $^0/_{00}$ SMOW. The δ ^{18}O of SO_4^{2} in seawater was not constant in the past. Pronounced variations exist throughout geologic time and found in all major marine evaporite deposits. The range of δ ^{18}O of SO_4^{2} in marine sulphate has varied about 17 $^0/_{00}$ in precambrian time (900-600 millions of year in the past) to 10 $^0/_{00}$ in tertier time (100 millions of year in the past) [2,4].

On the graph of δ ^{18}O in H_2O versus δ ^{18}O in SO_4^{2}, in the absence of isotope exchange, processes

---

* Corresponding author. Tel/Fax : 021-7690709
Email address : ristinpi@batan .go.id

involving H_2O alone (dilution and evaporation) move point horizontally. Evaporation process cause more enriched value in $\delta\ ^{18}O$ whereas dilution process causes more depleted $\delta\ ^{18}O$. Both processes are influenced by atmospheric temperature. At higher temperature, ^{16}O isotope is easier to move from liquid phase to vapor phase than ^{18}O so that the remaining liquid phase has an enriched value of ^{18}O (or $\delta\ ^{18}O$ is much larger) [2,5].

Processes involving SO_4^{2-} alone (crystallization, adsorption and reduction) move the point vertically. Combinations of the above processes can move point in any direction. Some shifts will be minor in comparison to the others. In subsurface anaerobic environments, SO_4^{2-} reduction may be extensive with large accompanying isotope fractionation. The largest shifts in both direction and magnitude are expected from oxidation of sulphides and other S-species involving meteoric water at higher latitude [2,6].

The aim of this experiment is to know the processes probably influencing $\delta\ ^{18}O$ composition in groundwater sulphate and to determine sulphate origins in deep groundwater of Jakarta and its surroundings. Groundwater samples were taken from bore wells at the depth of 40-140 m, which are classified to upper confined groundwater. Sampling sites are mostly located in industrial areas. Sampling activities were conducted in dry season from August to September 1998. The distances between two sampling sites are approximately 5 km.

EXPERIMENTAL SECTION

Materials

The materials used in this experiment were $HgCl_2$, liquid nitrogen, acetone p.a, CO_2 gas high pure 99.9%, graphite, distilled water, $BaCl_2$ 10%, dry ice, Cl^- anion exchange resin (Dowex 50-100 mesh), HCl 6 M, NaCl 1 M.

Instruments

The equipments used in this experiment were Sira 9 ISOGAS mass spectrometer and isoprep O-18 line, sulphate preparation line, analytical balance, pH meter, digital thermometer, agate mortar, hot plate, platinum foil, dewar, 10-L plastic bottles, glass column: internal diameter 28 mm and height 200 mm.

Procedures

Sampling methods

Water samples were collected in 20 mL glass vial, for O-18 in water analysis. These samples must be sealed tightly to prevent evaporation process. For O-18 in dissolved sulphate, water samples were collected in 10-L plastic bottles or depend on their sulphate content, then 1 mg $HgCl_2$ was added for sulphate preservation from bacterial activities.

Preparation of CO_2 gas for O-18 isotope analysis in dissolved sulphates [7].

O-18 in dissolved sulphates from groundwater was analyzed according to Rafter method. For pretreatment purpose, sulphate concentration should be determined previously. If sulphate concentration in fluids is higher than 50 ppm, the samples can be directly precipitated as $BaSO_4$ by adding $BaCl_2$ whereas the low sulphate samples should be passed through the ionic resin column. Ionic resin column was conditioned by eluting 150 mL of HCl at a rate of 4-5 ml/min and then 300 mL of distilled water at the same rate. About 10 L of filtered sample was passed through the column at flow rate of 150-200 mL/min, allowing the sulphate compound to be absorbed completely. Three hundreds mililiters of NaCl was eluted through column at a flow rate of 1 mL/min in order to dissolve the absorbed sulphate then this concentrated sulphate was put in beaker glass. This sample was reduced its pH to 4 by dropping 10 % HCl and heated (90 – 100 ^oC) to remove CO_2 gas. Amount of $BaCl_2$ was added to form the white precipitation of $BaSO_4$.

About 50 mg precipitation of $BaSO_4$ was grinded with graphite. This sample was transferred to platinum boat and placed to reactor in sulphate preparation line. Reduction process was taken place at the temperature of 1200 ^oC under vacuum condition, its reaction as follow:

$$BaSO_4 + 3C \rightleftarrows BaS + CO_2 + 2CO$$

The released water vapor was trapped using acetone-dry ice mixture (about -78 ^oC) whereas CO and CO_2 gas were passed and trapped in a discharge tube which was placed in liquid nitrogen dewar (-196 ^oC). Conversion of CO to CO_2 gas was taken place under high voltage current (1.2 KV), which passed through two platinum electrodes in the discharge tube. The evolved CO_2 gas was transferred to a sample bottle and ready to be injected to mass spectrometer.

Analysis of O-18 isotope in water [8]

O-18 isotope in water was analyzed according to Epstein-Mayeda method. Analysis was done on carbon dioxide released from O-18 isotopic exchange reaction between water samples and CO_2 reference. About 2 ml water samples in vessel reaction, which has been evacuated, were flown by CO_2 gas reference and shaked for overnight at constant temperature (usually 25^0C) in order to equilibrate both compounds. The following isotopic exchange reaction will occur:

$$H_2{}^{18}O_{liquid} + C^{16}O_{2\ gas} \rightleftarrows H_2{}^{16}O_{\ liquid} + C^{18}O_{2\ gas}$$

The reaction above was occurred in isoprep-18 consisting of 24 vessel reactions in water bath and connected directly to mass spectrometer. The result was isotopic ratio of oxygen-18 related to oxygen-16.

***Measurements of isotopic ratio value* [3,5,7]**

Isotopic ratio value was expressed with (delta) notation in per mill ($^{0}/_{00}$) and defined as follows:

$$\delta(^{0}/_{oo}) = \frac{R_{sample} - R_{reference}}{R_{reference}} \text{ x } 1000$$

Where the “R” is, in the case of water, the $^{18}O/^{16}O$. As reference for oxygen in water are SMOW international standard (Standard Mean Ocean Water). Whereas $^{18}O/^{16}O$ isotope ratio of sulphates or carbonates should be compared to PDB-barium carbonates international standard (Pee Dee Balemnitella). To simplify data interpretation, mostly, this value was related to $^{18}O/^{16}O$ in water samples that has SMOW standard. Conversion of PDB to SMOW standard followed to this equation:

$$\delta\, ^{18}O_{\,sample}\, (^{0}/_{00})_{SMOW} = \delta\, ^{18}O_{\,sample}\, (^{0}/_{00})_{PDB} + 1.04143$$

RESULT AND DISCUSSION

This experiment was successfully carried out with helping Directorate of Environmental Geology- Bandung that has supplied for bore wells data, depth and locations, and actively participated in collecting groundwater samples. The depths and locations of bore wells in Jakarta are shown at Table 1 whereas points for sampling locations are mapped at Fig 1. Previously, the other experiment has been conducted by Wandowo, et.al [9] and declared that Jakarta upper confined groundwater is supplied by meteoric water infiltrating at the altitude of 130 – 280 m. This area is located in surroundings of Sawangan-Depok and Bogor. This conclusion was based on the similarity of $\delta\, ^{18}O$ and $\delta\, ^{2}H$ (deuterium) value in H_2O between Jakarta deep groundwater and meteoric water at this altitude.

Beside oxygen isotope in water, oxygen isotope in sulphate was also analyzed in this experiment. As mentioned above, the relationship between both data can be used to understand a process or reaction influencing in oxygen isotope distribution in groundwater sulphate. The results of $\delta\, ^{18}O\, (SO_4^{2-})$ and $\delta\, ^{18}O\, (H_2O)$ analysis from deep groundwater of Jakarta are presented in Table 2. It is clearly showed that $\delta\, ^{18}O\, (H_2O)$ values are more quite narrow in the range of -5,04 $^{0}/_{00}$ to -6,65 $^{0}/_{00}$ SMOW than $\delta\, ^{18}O\, (SO_4^{2-})$ values which have a wider range of +8,3 $^{0}/_{00}$ to +17,4 $^{0}/_{00}$ SMOW.

Those values of $\delta\, ^{18}O\, (H_2O)$ in turn depend on the latitude, the degree of continentally, and the altitude at which recharging precipitation fell. At higher altitudes, higher latitudes and continental areas have more negative $\delta\, ^{18}O\, (H_2O)$ values or more depleted [5]. The range of $\delta\, ^{18}O\, (H_2O)$ values for particular area, except in geothermal area, is commonly quite narrow because there are not a subsurface boiling, steam separation or exchange oxygen isotope process [2]. It can be seen at Table 2, Jakarta located near the equator (lower latitude) and island area has $\delta\, ^{18}O\, (H_2O)$ values in the range of –5.08 $^{0}/_{00}$ to –6.65 $^{5}/_{00}$ SMOW. Those values greatly affected to the extent of $\delta\, ^{18}O\, (SO_4^{2-})$ values. The values of $\delta\, ^{18}O\, (SO_4^{2-})$ in Jakarta deep groundwater fall in the range of 8.36 $^{0}/_{00}$ to 16.65 $^{0}/_{00}$ SMOW. The widest range of $\delta\, ^{18}O\, (H_2O)$ and $\delta\, ^{18}O\, (SO_4^{2-})$ values is expected at higher latitudes with a high degree of continentally, particularly when meteoric water with highly negative $\delta\, ^{18}O\, (H_2O)$ recharges local groundwater systems [2].

Table 1. Depth and location data from bore wells in Jakarta deep groundwater

No	Sample code	Location	Address	Depth (m)
1	JUT-16	PT.Kian Hin	Jl.Jembatan II Pejagalan-Penjaringan	83-132
2	JUT18	PT.Tancho Ind.	Jl.Yos Sudarso- Sunter-Tanjung Priok	117-119
3	JUT-19	PT. Diamond	Jl.Pasir Putih Raya-Ancol-Pademangan	128-137
4	JBB4	PT.ABC Battery	Jl. Daan Mogot-Kd Kaliangke-Cengkareng	149-162
5	JUB21	PT.CPP Lion Star	Jl.Sudyatmo-Kamal Muara-Penjaringan	137-163
6	JTT13	PT. Canada Dry	Jl.Bekasi Raya-Penggilingan-Cakung	123-153
7	JTT-14	PT. Wonderful	Jl.Pahlawan Revolusi-Klender-Duren Sawit	75-100
8	JTT-15	PT. Essense	Jl.Otista Raya-Bidara Cina-Jatinegara	60-100
9	JTT-16	PT. Susu Bendera	Jl.Lingkar luar-Kp.Rambutan –Ciracas	55-104
10	JST-15	PT. Trebor	Jl. Ps Minggu-Pejaten Barat-Ps.Minggu	55-94
11	JST-16	PT. Kaos Aseli	Jl. Supomo-Menteng Dalam-Tebet	52-130
12	JST-17	Lemigas	Jl.Panjang –Cipulir-Kebayoran Lama	118
13	BgT-22	PT.YKK Zipper	Jl.Bogor Raya-Sukamaju-Cimanggis	69-135
14	BgT-26	PT. Santa Rosa Ind	Jl. Hasyim Ashari-Cibinong-Bogor	120
15	TgT-12	PT. Yuasa Baterai	Jl. Thamrin-Cikokol-Tangerang	60
16	TgT13	Puribeta Real Estat	Jl. Cokroaminoto-Ciledug-Tangerang	130
17	BkT-6	PT.Peony Blanket	Jl. Sultan Agung-Kranji-Bekasi Barat	61-82

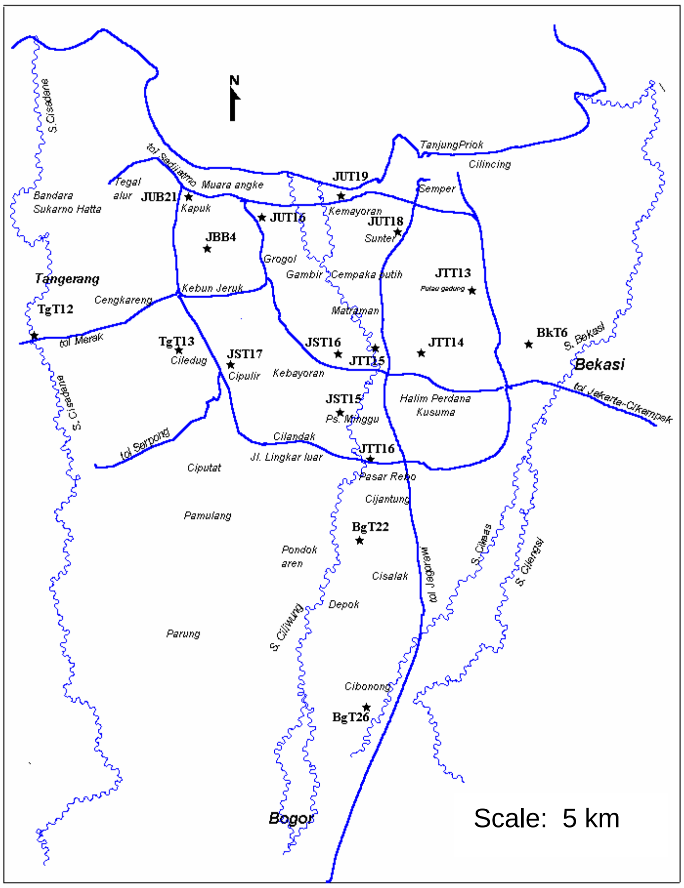

Fig 1. Map of collected deep groundwater in Jakarta and its surroundings

Table 2. $\delta\,^{18}O\ (SO_4^{2-})$ and $\delta\,^{18}O\ (H_2O)$ values from Jakarta deep groundwater

No.	Sample code	$\delta\,^{18}O\ (SO_4^{2-})$ $^0/_{00}$ SMOW	$\delta\,^{18}O\ (H_2O)$ ($^0/_{00}$ SMOW
1.	JUT-16	9,611	-6,44
2.	JUT-18	14,941	-6,09
3.	JUT-19	13,572	-5,86
4.	JBB-4	11,156	-5,28
5.	JUB21	9,702	-5,08
6.	JTT-13	17,196	-5,04
7.	JTT-14	14,519	-6,17
8.	JTT-15	17,394	-5,57
9.	JTT-16	16,144	-6,24
10.	JST-15	8,365	-6,00
11.	JST-16	10,458	-6,65
12.	JST-17	16,654	-6,14
13.	BgT-22	16,082	-6,06
14.	BgT-26	10,843	-5,37
15	TgT-12	8,510	-6,2
16	TgT-13	10,895	-6,00
17.	BkT-6	12,374	-5,62

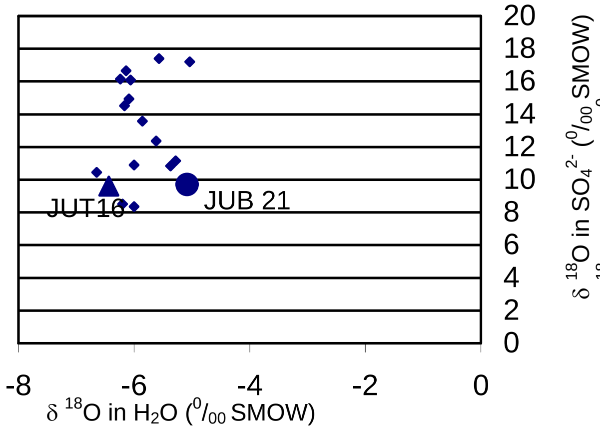

Fig 2. Relationship between $\delta\,^{18}O$ in water and $\delta\,^{18}O$ sulphate from Jakarta deep groundwater

Plotting between $\delta\,^{18}O\ (H_2O)$ and $^{18}O\ (SO_4^{2-})$ values is given at Fig 2. The distribution of those values seemly move in vertical position or $\delta\,^{8}O\ (H_2O)$ values are more constant than $\delta\,^{18}O\ (SO_4^{2-})$ values. It means that deep groundwater of Jakarta, with the depth of 55 m to 150 m, has not occurred an evaporation process during moving from recharge area to sampling points but dissolution by local meteoric water may effect to those values. An impermeable layer is stretched out on this aquifer so that evaporation process can't occur. Evaporation can move $\delta\,^{18}O\ (H_2O)$ values in positive direction or result enriched values.

The vertical position as shown at Fig 2 defined that deep groundwater sulphate of Jakarta is dominantly derived from the dissolution of marine evaporate sulphate. Mostly, $^{18}O\ (SO_4^{2-})$ values of this groundwater are in the range of its source, marine evaporite sulphate, which has $^{18}O\ (SO_4^{2-})$ value of $10\,^0/_{00}$ to $17\,^0/_{00}$ SMOW [1]. As we know that Jakarta has flat land areas with the north part is covered by shores so that its lithological composition in surficial aquifer and bedrock aquifer is greatly made of sedimentary rock from marine sediment material. Its surficial aquifer is mainly composed by alluvial deposit consisting of clay, sand, gravel and boulders covering to coastal, river and swamp deposit. The north part is formed from coastal deposits that consist of fine to course sand and supposed its formation come from marine environment. Its bedrock aquifer is composed mainly during Pliocene and Miocene period in the environment of open shallow marine. But, some areas are made of sedimentary from swamp, old river of Cisadane and volcanic rock [10].

Sampling point of JUT-16 which lies around Pejagalan-Penjaringan – North Jakarta has $\delta\,^{18}O\ (SO_4^{2-})$ value of 9.611 $^0/_{00}$ SMOW. This value was greatly closed to $\delta\,^{18}O\ (SO_4^{2-})$ value of modern seawater that has homogenous value of 9.5 $^0/_{00}$ [1]. It indicated that seawater intrusion has taken place in this groundwater to the depth of 83-132 m. This indication was also supported by its high chloride concentration of 3353.9 ppm [9].

Phenomenon of seawater intrusion might also occur in JUB-21, namely around Kamal Muara-Penjaringan – North Jakarta, that has $\delta\ ^{18}O\ (SO_4^{2-})$ value of 9.702 $^0/_{00}$ SMOW. However, its lower chloride concentration of 254.6 ppm [9] indicated that seawater intrusion in this area was not much higher than that occurred in Pejagalan. Point of JBB-4 located in Kedaung Kaliangke-Cengkareng has chloride content of 510 ppm [9] but its $\delta\ ^{18}O\ (SO_4^{2-})$ value of 11.156 $^0/_{00}$ was higher than that of modern seawater. It was probably caused by mixing process between seawater and other sulphate sources coming from industrial waste.

In contrast to JUT-18 and JUT-19 located around Sunter-Tanjung Priok and Ancol-Pademangan, its chloride concentration was 22.4 ppm and 122.7 ppm [9] whereas its $\delta\ ^{18}O\ (SO_4^{2-})$ value was 14.94 $^0/_{00}$ and 13.57 $^0/_{00}$, respectively, as shown at Table 2. Those data showed that seawater intrusion might not yet occur in their deep groundwater although both areas are located near to coastal.

The extent of vertical position can be caused by dissolution of marine evaporite sulphate, reduction of some of sulphate followed by oxidation of the product sulphides and subsurface oxidation of organic sulphur and heavy metal (such as Zn, Cu, Pb, U and Fe) sulphides [2]. The lower $\delta\ ^{18}O\ (SO_4^{2-})$ value in groundwater sulphate reflects reduction of original marine sulphate, followed by oxidation of part of the product sulphides (HS^-) as that might occur in JST-15 and TGT-12. The lowering of $\delta\ ^{18}O\ (SO_4^{2-})$ depends on the proportion of secondary SO_4^{2-}, the negative value of $\delta\ ^{18}O\ (H_2O)$ and the degree to which bacterial oxidation is involved.

Beside $\delta\ ^{18}O\ (H_2O)$, the atmospheric oxygen having $\delta\ ^{18}O\ (O_2)$ value of 23 $^0/_{00}$ can have an influence to the extent of $\delta\ ^{18}O\ (SO_4^{2-})$ composition [1]. The $\delta\ ^{18}O\ (SO_4^{2-})$ values may be a mixture of these two end members. Fig 3 showed that $\delta\ ^{18}O\ (SO_4^{2-})$ values of Jakarta deep groundwater mostly spread in the range of marine evaporite sulphate. This figure also defined that contribution of oxygen from Jakarta deep groundwater, $\delta\ ^{18}O\ (H_2O)$ value is -5,04 $^0/_{00}$ to -6,65 $^0/_{00}$ SMOW, in the sulphide oxidation reaction has a narrow range from 0% to 12%. These lower percentages of water exhibited that molecular oxygen from atmosphere more affected to $\delta\ ^{18}O\ (SO_4^{2-})$ in most Jakarta deep groundwater.

Taylor suggests that oxidation of heavy metals (example FeS_2) in subsurface water is controlled by bacteria catalyst as the following reactions [11] :

(1) $FeS_2 + 4Fe^{3+} + 8H_2O \longrightarrow$
$5Fe^{2+} + 2SO_4^{2-} + 6H^+$ abiological

(2) $Fe^{2+} + 1/4O_2 + H^+ \longrightarrow$
$Fe^{3+} + ½\ H_2O$ Thiobacillus ferrooxidans

(3) $FeS_2 + 7/2O_2 + H_2O \longrightarrow$
$Fe^{2+} + 2SO_4^{2-} + 2H^+$ Thiobaccillus thiooxidans

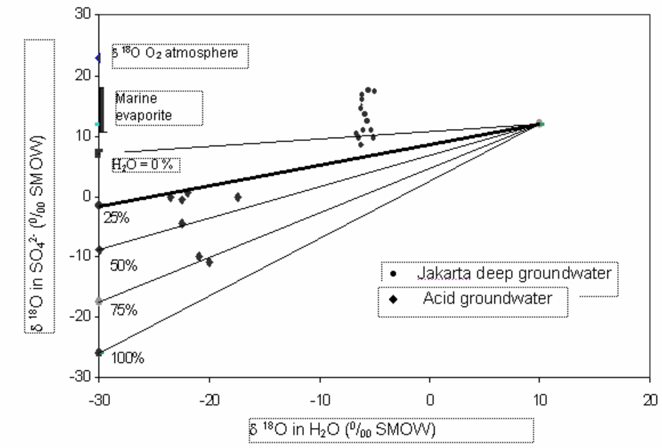

Fig 4. The oxygen isotopic composition of sulphate in Jakarta deep groundwater according to the percent water in the oxidation reaction (as modified by van Everdingen)

Seemly, reaction 3 may be an important sulphide oxidation to contribute considerable amount of sulphate to deep groundwater of Jakarta and produce gypsum or anhydrite minerals. The most common case in sulphate groundwater predicts the contribution from water to be 0% to 25% for non-saturated condition and 25% to 75% for saturated condition [2].

CONCLUSION

The $\delta\ ^{18}O\ (H_2O)$ values from groundwater at the depth of 40 to 140 m in Jakarta area and its sorroundings have a narrow range from -5,04 $^0/_{00}$ to –6,65 $^0/_{00}$ SMOW whereas their $\delta^{18}O\ (SO_4^{2-})$ values have a wider range from +8,3 $^0/_{00}$ to +17,4 $^0/_{00}$ SMOW. The more constant values of $\delta\ ^{18}O\ (H_2O)$ performed that evaporation effects might not occur in the deep groundwater. Based on the similarity between $\delta^{18}O\ (SO_4^{2-})$ values of deep groundwater and that of marine evaporite sulphate rocks, it is supposed that sulphate in Jakarta deep groundwater was derived from dissolution of this rocks. There was an indication of seawater intrusion around Pejagalan and Kamal Muara Penjaringan area based on their $\delta^{18}O\ (SO_4^{2-})$ values. The contribution of oxygen from water in sulphide oxidation reaction ranged 0% to 12% suggesting that oxygen sulphate was mainly derived from atmospheric molecular oxygen.

ACKNOWLEDGEMENT

The author wishes to thank to Directorate of Environmental Geology, Bandung for their supports concerning in bore well data supplies and water collecting activities.

REFFERENCES

1. Clark, I and Fritz, P., 1997, *Groundwater Quality in Environmental Isotopes in Hydrogeology*, Lewis Publishers, Boca-Ratan-New York, 137
2. Krouse, HR and Van Everdingen, R, 1985, *Nature*, 315, 395-396
3. Hoefs, J., 1980, *Stable Isotope Geochemistry*, Springer-Verlag, Berlin, 18.
4. Leone G, Ricchiuto TE and Longinelli A, 1987, Proceedings of an Advisory Group Meeting at 17-20 June 1985, International Atomic Energy Agency, Vienna, 5-14
5. IAEA,1981, D*euterium and Oxygen-18 in water cycle* in *Stable Isotope in Hydrology-Technical Report Series 210*, International Atomic Energy Agency, Vienna, 103
6. Krouse, HR., 1987, Proceeding of an Advisory Group Meeting at 17-20 June 1985, International Atomic Energy Agency , Vienna,19-20
7. Rafter, TA ., 1967, *New Zealand J. Sci.,*10, 493-510
8. Epstein, S and Mayeda, TK.,1959, *Geochim.Cosmochim Acta*, 4, 10, 213-224
9. Wandowo, 2000, *Laporan Akhir Riset Unggulan Terpadu V Bidang Teknologi Perlindungan Lingkungan* 1997-2000, Kantor Menteri Riset dan Teknologi - Dewan Riset Nasional.
10. Dinas Geologi dan Tata Lingkungan, 1994, Dinas Pertambangan DKI Jakarta, Jakarta.
11. Taylor, BC., Wheeler, MC., and Nordstorm, DK, 1984, *Nature*, 308, 538-541