SELECTED HYDROGEOCHEMISTRY OF PORING HOT SPRING (RANAU, SABAH) WITH APPLICATION TO GEOTHERMOMETRY

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THIS THESIS IS SUBMITTED TO FULFILL THE PARTIAL REQUIREMENT TO OBTAIN A BACHELOR OF SCIENCE (HONS) DEGREE

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DECLARATION

I hereby declare that this work is a result of my own effort except citations, references and abbreviations which sources have been clarified.

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ABSTRACT

This study was done in the Poring Hot Spring area in Ranau, Sabah, Malaysia. Specifically, this study consists of (i) the temperature and pH measurement, (ii) the analysis of geothermal related elements in the fluid of the hot spring and (iii) the application of chemical geothermometers for the estimation of reservoir temperatures. The elements analysed in this study are Na, K, Ca, Mg, Li and Si while SiO_2 values were calculated by the gravimetric method. The hot spring water was sampled and preserved according to guidelines provided by APHA (1998). The analysis of the elements Na, K, Ca and Mg was done through flame atomic absorption spectroscopy. Li and Si on the other hand was analysed by the inductively coupled plasma method. From the surface study, the highest temperature and pH was found to be 60.5 °C and pH 8.23 respectively while the lowest values of temperature and pH are 56.8 °C and pH 8.07 respectively. The mean for the temperature and pH is 59 °C and pH 8.14 respectively while the RSD is 2.67 % and 0.89 % respectively. For the geochemistry, concentrations of the selected elements in all springs are close to each other with exception to Si from Spring 5 where the value is 33.8 mg/L. This may be due to silification. The mean concentration for Na, K, Ca, Mg, Li, and Si are 312.75, 12.28, 4.86, 1.47, 0.83 and 38.56 mg/L respectively while their RSD are 5.41, 9.36, 11.11, 18.37, 7.22 and 8.95 % respectively. The Quartz-no steam loss geothermometers which is believed to be best applied in this study yielded values of 126.26, 130.13, 130.13 and 119.85 °C respectively for Springs 1 – 5. The Na/K (Fournier) and Na-K-Ca geothermometers yielded overly high temperatures while the *ά*-Cristobalite, *β*-Cristobalite and amorphous silica geothermometers produced temperatures that were too low. The conclusion that can be drawn is that all springs that were studied originated from the same low-enthalpy reservoir (119.85 – 130.13 °C) and the hot springs are best suited for recreational activities.

HIDROGEOKIMIA TERPILIH MATA AIR PANAS PORING (RANAU, SABAH) DENGAN APLIKASI GEOTERMOMETRI

ABSTRAK

Kajian ini telah dibuat di kawasan Mata Air Panas Poring di Ranau, Sabah, Malaysia. Secara spesifik, kajian ini merangkumi (i) ukuran suhu dan pH, (ii) analisis unsur-geothrma dan (iii) aplikasi geotermometer kimia untuk anggaran suhu takungan geoterma. Unsur yang dianalisis dalam kajian ini adalah unsur Na, K, Ca, Mg, Li, dan Si manakala nilai SiO_2 dikira menggunakan kaedah gravimetrik. Air mata air panas disampel dan diawet berdasarkan garis-garis panduan daripada APHA (1998). Analisis unsur Na, K, Ca dan Mg dibuat melalui kaedah spektroskopi serapan atom. Li dan Si pula dianalisis menggunakan kaedah "*inductively coupled plasma*". Dari kajian ini, nilai suhu dan pH tertinggi yang direkod adalah 60.5 °C dan pH 8.23 masing-masing manakala nilai suhu dan pH terendah adalah 56.8 °C dan pH 8.07. Purata suhu dan pH adalah 59 °C dan pH 8.14 masing-masing manakala sisihan piawai relatif (SPR) adalah 2.67 % dan 0.89 % masing- masing. Dalam aspek geokimia, kepekatan unsur-unsur yang terpilih dalam setiap mata air adalah serupa dengan pengecualian kepada unsur Si dari mata air Spring 5 yang nilainya 33.8 mg/L. Ini mungkin disebabkan oleh proses silifikasi. Purata kepekatan untuk unsur Na, K, Ca, Mg, Li dan Si adalah 312.75, 12.28, 4.86, 1.47, 0.83 dan 38.56 mg/L masing-masing manakala SPRnya adalah 5.41, 9.36, 11.11, 18.37, 7.22 dan 8.95 % masing-masing. Geotermometer kuarza-tanpa kehilangan stim yang dipercayai paling sesuai untuk diaplikasikan dalam kajian ini memberi nilai 126.26, 130.13, 130.13 and 119.85 °C masing-masing untuk mata air Spring 1 – Spring 5. Geotermometer Na/K (Fournier) dan Na-K-Ca memberi nilai suhu yang terlalu tinggi manakala geotermometer *á*-Cristobalite, *β*-Cristobalite dan "amorphous silica" memberi nilai suhu yang terlalu rendah. Kesimpulan yang boleh didapati ialah kesemua mata air panas yang dikaji berasal daripada takungan geoterma bertenaga rendah (119.85 – 130.13 °C) yang sama. Penggunaan yang paling sesuai untuk kesemua mata air panas ini adalah aktiviti rekreasi.

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LIST OF SYMBOLS

t	temperature
$<$	less than
$=$	less than or equals to

LIST OF UNITS

m	metre(s)
km	kilometre(s)
$mile^2$	mile square
L	litre(s)
mL	milimetre(s)
$mg\ L^{-1}$	milligram per litre
°C	degree centigrade
pH	pH
MPa	megapascal
$kJ\ kg^{-1}$	kilojoule per kilogram
Pn	Pn
D	darcy

LIST OF ABBREVIATIONS

UMS	Universiti Malaysia Sabah
DSIR	Department of Scientific and Industrial Research
APHA	American Public Health Association
CSE-NRC	Committee on the Science of Earthquakes, National Research Council
FAAS	Flame Atomic Absorption Spectrophotometer
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectroscopy
PE	polyethylene
PP	polypropylene
HNO_3	nitric acid
Na	sodium
K	potassium
Ca	calcium
Mg	magnesium
Li	lithium
Si	silicon
SiO_2	silica
He	helium
et al	and others
etc	etcetera
d^{18}	fractionation of oxygen
ND	not detected
NM	not measured
SD	standard deviation

RSD	relative standard deviation
RAM	relative atomic mass
RFM	relative formula mass
C. C	correlation coefficient
R	replicate
$\Delta^{18}O(SO_4^{-} - H_2O)$	sulphate oxygen isotope geothermometers
MMD	Malaysian meteorological Department
MGD	Mineral and Geoscience Department

LIST OF FORMULAS

Formula			Page
(2.1)	$t°C = \dfrac{1217}{\log(Na/K) + 1.483} - 273.15$	Na/K (Fournier) geothermometer	27
(2.2)	$t°C = \dfrac{855.6}{\log(Na/K) + 0.8573} - 273.15$	Na/K (Truesdell) geothermometer	27
(2.3)	$t°C = \dfrac{1647}{\log(Na/K) + \beta[\log(vCa/Na) + 2.06] + 2.46} - 273.15$	Na-K-Ca geothrmometer	27
(2.4)	$t°C = \dfrac{2200}{\log(vMg/Li) + 5.47} - 273$	Mg/Li geothermometer	27
(2.5)	$t°C = \dfrac{1309}{5.19 - \log C} - 273.15$	quartz-no steam loss geothermometer	27
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(2.11)	$1000 \ln \acute{\alpha} = 2.88(10^6\, T^{-2}) - 4.1$ $\acute{\alpha} = \dfrac{1000 + d^{18}O(HSO_4^-)}{1000 + d^{18}O(H_2O)}$ and T = °K	$\Delta^{18}O(SO_4^{=} - H_2O)$ geothermometers	27
(A1)	$\Delta t_{Mg} = 10.66 - 4.7415R + 325.87(\log R)^2 - 1.032 \times 10^5(\log R)^2/T + 1.605 \times 10^7(\log R)^3\, T^2$	Mg calculation for the Na-K-Ca geothermometer for 5 = R = 50	96

(A2)	$\Delta t_{Mg} = -1.03 + 59.971 \log R + 145.05(\log R)^2 - 36711(\log R)^2 / T - 1.67 \times 10^7 \log R / T^2$	Mg calculation for the Na-K-Ca geothermometer for $R < 5$	96

CHAPTER 1

INTRODUCTION

1.1 Geothermal Energy and Systems

The earth is known to possess its own internal heat energy. Several theories have been proposed pertaining to the source of the internal heat of the earth. The most credible and accepted theory today is the big bang theory that explains the formation of the solar system which includes the earth. Generally, the earth's heat comes from and is sustained till today by radioactive elements actively undergoing fusion and fission which will be explained in detail in Chapter 2.

The core of the earth has been estimated to have temperatures from 5000 to 6000 °C while the mantle has been estimated to reach temperatures of 4000 °C (Chan, 1999). With such magnitude and amount of heat energy stored deep within the earth, some form of manifestations must take place to vent out this heat energy. Among such manifestations are geysers, hot springs and fumaroles. These manifestations do not originate directly from the core and mantle itself, but from various types of geothermal systems.

The term geothermal refers to things of or relating to the heat in the interior of the earth. A geothermal system is classified and defined from a geological and hydrological aspect as well as from the aspect of its heat transfer characteristics. Although the term is generally used to denote the internal energy of the earth, more specifically it refers to a system or location where the earth's heat is concentrated enough to be used or exploited as an energy resource (Rybach and Muffler, 1981). The different types of geothermal systems and its respective principles will be explained further in Chapter 2.

1.2 Geothermal Manifestations

Among some of the geothermal manifestations are hot springs, geysers, fumaroles, boiling mud, and even volcanoes. The focus of this study will be on hot springs only which is simply hot water discharged from the earth. A geyser is the discharge of hot water or steam or a combination of both in a pressurised and sometimes violent stream. Fumaroles are steam discharges that are not violent unlike geysers. Boiling mud is a similar system to that of a hot spring with difference only in its medium which is mud and not water. Volcanoes are the most violent manifestation of all discharging steam, ash, sulphurous gases and magma (Goudie, 2004).

Hot Springs are common compared to the rest of the geothermal manifestations. In Sabah, there are three districts with the occurrence of hot springs which are Semporna, Tawau, and Ranau. This study is done on the Poring Hot Springs of Ranau which are of a lower enthalpy compared to those at Semporna and Tawau (Lim, 1991).

1.3 Background of study

This study is done in the Poring Hot Spring area in Ranau, Sabah, Malaysia. Specifically, this study consists of the analysis of geothermal related elements in the fluid of the hot spring. Studies of this kind have been done extensively around the world. Most of the geothermal exploration projects or industrial studies in the world will and must include the component of geothermal fluid analysis as the data will be used to calculate the reservoir temperature by means of chemical geothermometers (Geothermometry, 2008).

The determination of reservoir temperatures is important for the determination of the possible exploitable use of a particular geothermal system. For electricity generation, the heat must be sufficient and the reservoir must be within the drillable depth of 3 km or less due to the economic cost that increases with depth (Rybach, 1981). Reservoirs of lower enthalpy on the other hand can be useful in direct applications and municipal uses such as space heating or balneology.

1.4 Study Area

The study site, Poring Hot spring is located approximately 11 km from Ranau town. This area has been developed for tourism and recreational purposes with many facilities. Among the facilities in the area is the butterfly farm, the Poring Orchid Observation Centre, the Kipungit Waterfall, a tropical garden, the Poring Canopy Walkway, accommodation and campsites and hot spring bathtubs. Visitors of this place include locals as well as foreign tourists. The number of visitors to Poring Hot

Spring throughout the year 2008 is tabulated in Table 1.1. A detailed statistics from year 2007 to 2009 is provided in Appendix D.

Table 1.1: Visitors to Poring Hot Spring in the year 2008
(Source: Sabah Parks Archives)

Month	Visitors		Total
	Locals	Tourist	
January	9209	2445	11651
February	15265	3008	18273
March	14430	1880	16310
April	9434	1571	11005
May	16112	2350	18462
June	22167	2269	24436
July	10555	3289	13844
August	20480	4647	25127
September	7288	2802	10091
October	19660	2273	21933
November	19820	2132	21952
December	47141	2103	49244
Total	211558	30769	242327

According to the DSIR (1979), Sabah is predominantly formed and covered by sedimentary and igneous rocks. No active volcanoes are found in Sabah. The occurrence of hot springs indicates the near igneous activity in this state. Nonetheless, a very young age is recorded for rocks here with pyroclastics in Tawau dated at most 27,000 years. Minor seismicity in the Darvel Bay region which caused a damaging earthquake in 1976 are one of the signs of still persisting tectonic activities. Clearly, the DSIR (1979) points out that Sabah has traces of volcanic activity.

The origin of Poring hot springs has to be traced back to the origin of Ranau, the place in which Poring itself is in. The geological properties of the whole area of Ranau including the Poring hot springs are very much characterised by Mount Kinabalu. This mountain of 4095 m consists predominantly of granitic and granodiorite rock types with the east side being the peridotite ultrabasic rocks (Wong and Chan, 1997). The mount and its other similar landforms around the area are believed to be formed by a large arising batholith from below with a size of up to 500 mile^2 in extent (DSIR, 1979). In fact, a large part of Ranau with its elevation is caused by this batholith intrusion.

The origin of the hot springs' heat can be attributed to the batholith intrusion. DSIR (1979) stated that the underground heat source of Poring is a residual heat that comes from the initial heat of the batholith as it intrudes out. This heat therefore lasted till this day although a slight decline has been observed compared to the early days.

Despite of the batholith intrusion, the origin of the hot springs goes further than just the origin of the underground heat. The working fluid, water, which is needed to transport this heat upwards, has had several theories concerning its origin. Kenji Wakita, Geological Superintendent for the Mamut mine and formerly a geothermal geologist in DSIR (1979) proposed that the springs are present due to deep circulation of meteoric waters which transports some of the original heat in the batholiths to be convected to the surface. Another possibility is that the presence of nearby hypabyssal rocks that may allow meteoric waters to penetrate to considerable depth where it is heated at regions of abnormal temperatures (DSIR, 1979). This classifies the Poring hot springs as a tectonic hot spring and not a magmatic hot spring. Hot springs of this type are normally found close at a major fault and being far away or isolated from active or recent volcanism. This is further supported by the fact that the compositions of the Poring hot springs are very similar to that of the so-called tectonic hot springs of New Zealand (DSIR, 1979).

1.5 Aim and Objectives of Study

The primary aim of this study is to estimate the reservoir temperatures of Poring Hot Spring by means of chemical geothermometers. This information can then be used to provide useful suggestions on the optimal usage of the hot springs.

Among the objectives of this study are:

i. To study the surface of the hot springs and obtain information on the temperature and pH.

ii. To analyse the concentration of geothermal elements (Sodium, Na; Potassium, K; Calcium, Ca; Magnesium, Mg; Lithium, Li and Silicon, Si) in the waters of Poring Hot Spring.

iii. To determine reservoir temperatures by application of chemical geothermometers.

1.6 Significance of Study

The two primary information that was obtained in this study are the concentration of selected elements and calculated reservoir temperatures. The purpose of knowing the geochemistry of the hot springs fluid is in determining the suitability of usage by humans. For example, the utilisation of hot spring fluid for agricultural purposes is only advantageous if there are sufficient or considerable amount of macronutrient. The deficiency of macronutrient K for example causes tomato plants to have reduced photosynthesis rate (Behboudian and Anderson, 1990). Determination of the suitability for balneology also requires the chemical composition of the hot spring fluid to make sure that all chemicals are within the permissible levels.

Reservoir temperatures are used mainly for determining the suitability of a geothermal reservoir for power generation purposes. Even for power generation purposes, the enthalpy of the reservoir needs to be known to determine the best power generation cycles. Power generation via the binary cycle can utilise hot springs with outlet temperatures as low as 80 °C (Armstead, 1983). The enthalpy of the reservoir also reveals information on the sustainability of the geothermal system. With this, economical considerations can be made to whether the amount of power generated will justify the development cost (Armstead, 1983).

Even after development has been done on a certain geothermal area, the periodic monitoring of the chemical composition and reservoir temperatures are useful for detecting changes in the enthalpy or activity of the geothermal system (Armstead, 1983).

REFERENCES

Alden, A. 1997. *Earth's Formation in a Nutshell.* http://geology.about.com/od/nutshells/a/aa_earthbirth.htm.

APHA (American Public Health Association *et al.*). 1998. Standard Methods for the Examination of Water and Wastewater.

Armstead, H. C. H. 1978. Geothermal Energy, Spon, London,.

Armstead, H.C.H. 1983. *GEOTHERMAL ENERGY: Its past, present and future contributions to the energy needs of man, Second Edition.* E. & F. N. Spon, New York.

Arnett, B. 2006. *Earth.* http://www.nineplanets.org/earth.html.

Arnorsson, S. 1975. Application of the silica geothermometer in low temperature hydrothermal areas in Iceland. *American Journal of Science* **275**, pg 763-784

Behboudian, M. H. and Anderson, D. R. 1990. Effects of potassium deficiency on water relations and photosynthesis of the tomato plant. *Plant and Soil* **127** (1), pg 137-139

Bennett, J. P., and Wetmore, C. M., 1999. Geothermal elements in lichens of Yellowstone National Park, USA. *Environmental and Experimental Botany* **42**, pp 191-200

Benoit, W. R. 1978. The use of shallow and deep temperature gradients in geothermal exploration in northwestern Nevada using the Desert Peal thermal anomaly as a model, *Geothermal Resource Council Trans.* **2**, pg 45-46

Blackwell, D. D. and Morgan, P. 1976. Geological and geophysical exploration of the Marysville geothermal area, Montana, U.S.A. P*roceedings of the Second U.N. Symposium on the development and Use of Geothermal Resources*, San Francisco.

Blommaert, W., Vandelannoote, R., Sadurski, A., Van 't dack, L. and Gijbels, R., 1983. Trace-element geochemistry of thermal water percolating through a karstic environment in the region of Saint Ghislain (Belgium). *Journal of Volcanology and Geothermal Research* **19**, pg 331-348.

Bodvarsson, G. 1960. Exploration and exploitation of natural heat in Iceland. *Bulletin Volcanology* **23**, pg 241-250

Buntebarth, G. 1984. *Geothermics: An Introduction*. Springer-Verlag, Heidelberg.

Cheremisinoff, P. N. and Morresi, A.C. 1976. *Geothermal Energy Technology Assessment*. Technomic Pub Co, Lancaster.

Committee on the Science of Earthquakes, National Research Council (CSE-NRC). 2003. *Living on an Active Earth: Perspectives on Earthquake Science*. National Academies Press, New York.

Darling, D. 2008. *protoplanetary disk*. http://www.daviddarling.info/encyclopedia/P/ protoplandisk.html.

Department of Scientific and Industrial Research, New Zealand (DSIR). 1979. *Geothermal Resources in Sabah, East Malaysia, Reconnaissance*.

Dickson, M. H., & Fanelli, M., 2004. *IGA International Geothermal Association*. http://csmres.jmu.edu/geollab/fichter/PlateTect/heathistory.html.

Diment, W. H. 1980. Geology and Geophysics of geothermal areas. In A *Sourcebook on the Production of Electricity from Geothermal Energy,* J Kestin, R. D. Pippo, H. E. Khalifa, and D. W. Ryley, (Eds.), U,S Govenrment. Printing Office.

Discover Borneo » Tours & Activities » Mountains & National Parks. 2008. http://www.discoverborneo.com/tours_activities/mountains_national_parks.php.

Donati, J. 2005. *Magnetic field of FU Orionis*. http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/www.ast.obs-mip.fr/users/donati/press/fuori_eng.html.

Dotsika, E., Leontiadis I., Poutoukis D., Cioni R., Raco, B. 2006. Fluid geochemistry of the Chios geothermal area, Chios Island, Greece. *Journal of Volcanology and Geothermal Research* **154**, pg 237-250.

Dorman, A. 1997-2008. *adamdorman.com - Preview of Earth Cross Section*. http://www.adamdorman.com/preview.php?TableName=digital_media&image=48&page=1.

e-Borneo, 2007. Tropical Vacation in Sabah, Malaysia Borneo. http://www.borneo-tropical-vacation.com/index.html

Elert, G. 2009. Temperature at the Center of the Earth. http://hypertextbook.com/facts/1999/PhillipChan.shtml

Ellis, A. J. 1970. Quantitative interpretation of chemical characteristics of hydrothermal systems, *Geothermics*, Special Issue 2, **2**(1), pg 516-528

Ellis, A. J. and Mahon, W. A. J. 1967. Natural hydrothermal systems and experimental hotwater/rock interactions (Part 2). *Geochim. Cosmochim. Acta*, **31**, 519-539.

Ellis, A. J. and Mahon, W. A. J. 1977. Chemistry and Geothermal Systems, Academic Press, New York.

Fichter, L. S. 2000. *Heat history of the earth*. http://csmres.jmu.edu/geollab/fichter/PlateTect/heathistory.html.

Fournier, R. O. 1981. Application of Water Geochemistry to Geothermal Exploration and Reservoir Engineering. Cited in: Rybach, L. and Muffler, L. J. P. 1981. *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd.

Fournier, R. O. and Truesdell, A. H. 1970. Chemical indicators of subsurfce temperature applied to hot spring waters of Yellowstone National Park, Wyoming U.S.A. *Geothermics*, Special Issue 2, **2**(1) 529-535

Fournier, R. O. and Truesdell, A. H. 1973. An empirical Na-K-Ca geothermometer for natural waters, *Geochim. Cosmochim. Acta*, **37**, 1255-1275

Fournier, R. O., and Potter, R. W. II, 1979. Magnesium correction to the Na-K-Ca chemical geothermometer. *Geochim. Cosmochim. Acta*, **43**, 1543-1550

Formation of the Earth. 2008. http://zebu.uoregon.edu/ph121/l7.html.

Friedman, H., 2003. Polymorphs of Quartz.http://www.minerals.net/mineral/silicate/tecto/quartz/sio2poly.htm#Cristobalite

Gallagher, D. 1997. Flame Atomic Absorption Spectrometry. http://www.cee.vt.edu/ewr/environmental/teach/smprimer/aa/aa.html

Gennaro, M. D., Ferreri, M., Ghiara, M. R., and Stanzione, D. 1984. Geochemistry on Thermal Waters on the Island of Ischia (Campania, Italy). *Geothermics* **14** (4), pp 361-374

Geothermometry. 2008. http://www.science.uottawa.ca/~eih/ch9/9geoth.html..

Godwin, P. 1991. Poring Hot Spring Water Analysis. Mineral and Geoscience Department (Unpublished).

Goff, F., Gardner, J., Vidale, R. and Charles, R.O. 1985. Geochemistry and isotopes of fluids from Sulphur Springs, Vanes Caldera, New Mexico. *Journal of Volcanology and Geothermal Research,* **23**, pg 273--297.

Goudie, A., 2004. Encyclopedia of geomorphology. Routledge

Harvey, B. and Robert, J. T. (1997). Petrology (2nd edition ed.). New York: Freeman

Harry Chong Lye Hin and Mohd Noh Dalimin. 2000. Hot Springs at Tawau Hill Park, Sabah, Malaysia. *22nd New Zealand Geothermal Workshop*: 139-142.

Harry Chong Lye Hin and Mohd Noh Dalimin. 2000. Tawau Hill Park Springs, Sabah, Malaysia. *Geo-heat Center (Oregon Institute of Technology) Quaterly Bulletin,* **21**(4): 3-4.

Harry Chong Lye Hin and Mohd Noh Dalimin. 2001. The Andrassy Geothermal Prospect In Sabah, Malaysia. *23rd New Zealand Geothermal Workshop*: 99-103.

Harry Chong Lye Hin and Mohd Noh Dalimin. 2002. Andrassy Geothermal Prospect. *Annual Workshop Nsf 2002*: 410-412.

Iyer, H. M. 1975. Anomalous delays of teleseismic P-waves in Yellowstone National Park, *Nature*, **253**, 425-427

Iyer, H. M. Ppenheimer, D. H., and Hitchocock, T. 1978. Teleseismic P-delays at The Geysers-Clear Lake, California, geothermal region. *Geothermal Resources Council Trans.*, **2**, 317-319

JUPEM, Jabatan Ukur dan Pemetaan Malaysia, 2008.

Kharaka, Y. K., and Mariner, R. H., 1989. Chemical Geothermometers and Their Application to Formation Waters from Sedimentary Basins, Cited in: Naeser, N. D. and McCulloh, T. H. 1989. *Thermal History of Sedimentary Basins, Methods and Case Histories*. Springer-Verlag, New York.

Kundell, J. and Matlock, M. 2007. *Spring - Encyclopedia of Earth* http://www.eoearth.org/article/Spring.

La geothermie: Chauffage de logement 1977. Delegation Generale a la Recherche Scientifique et Technidue Publication, Paris

La geothermie en France, 1978. Pibl. Delegation aux energies nouvelles, Paris.

Lachenbruch, A. H. Sass, J. H. 1977. Heat flow in the United States and the thermal regime of the crust. Cited in: J. G Heacock (Ed.). The Earth's Crust, *American Geophyisal Union Monograph* **20**, Washington, 626-675.

Lim, P. S. 1991. Prospects and Potential Uses of Geothermal Resources in Sabah. *Proceedings of the 22nd Geological Conference-Technical Papers* 3.

Laughlin, A. W. 1981. The Geothermal System of the Jemez Mountains, New Mexico and Its Exploration. Cited in: Rybach, L. and Muffler, L. J. P. 1981. *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd.

Maklarin Lakim, 2008. Assistant Director of Sabah Parks. *Oral Communication*.

Mercado, S. 1970. High activity hydrothermal zones detected by Na/K, Cerro Prieto, Mexico. *Geothermics*, Special Issue 2, 1367-1376

Morey, G. W., Fournier, R. O. and Rowe, J. J. 1962. The Solubility of Quartz in Water in the Temperature Interval from 29 ° to 300 °C. *Geochim. Cosmochim Acta*, **26**, 1029-1043

Muffler, L. J. P. 1976. Tectonic and Hydrologic Control of the Nature and Distribution of Geothermal Resources. *Proc. of the Second U.N. Symposium on the Development and Use of Geothermal Resources*, San Francisco, 499-507.

NMSU, 2006. NMSU: AAS.http://www.chemistry.nmsu.edu/Instrumentation /NMSU_AAS.html

Occupational Safety and Health Administration (OSHA), 2002. Crystalline Silica Exposure" Health Hazard Information for General Industry Employees (OSHA 3176). http://www.osha.gov/Publications/osha3176.html

Ottlik, P., Galfi, J., Horvath, F., Korim, K., and Stegena, L. 1981. The Low Enthalpy Geothermal Resource of the Pannonian Basin, Hungary. Cited in: Rybach, L. and Muffler, L. J. P. 1981. *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd.

Jolyon, and Ralph, I. 2009. Mineralogy Database - Mineral Collecting, Localities, Mineral Photos and Data. http://www.mindat.org/index.php

Robinson, B.W. and Sheppard, D.S. 1986. A chemical and isotopic study of the Tokaanu-Waihi geothermal area, New Zealand. *Journal of Volcanology and Geothermal Research* **27**, pg 135-151.

Rybach, L. 1981. Geothermal Systems, Conductive Heat Flow, Geothermal Anomalies. Cited in Rybach, L. and Muffler, L. J. P. 1981. *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd.

Rybach, L. and MUFFLER, L. J. P., 1981. *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd.

Science Notes. 2008. http://www.stevenstanek.com/Science/Moon_Site/science.html #Earth.

Smith, R. L. and Shaw H. R. 1975. Igneous-related geothermal systems. Cited in: White, D. E. and Williams, D. L. (Eds.). *Assessment of Geothermal Resources of the United States-1975,* U.S. Geol. Survey Circ **726**, 58-83

Tanigawa, T. 2008. Migration of protoplanets: Effects on terrestrial planet formation. *Science Direct*, **56** (13) pg 1758-1763.

Techniques for Metal, 2009. http://72.14.235.132/search?q=cache:884DMCGu5q8J: www.nd.edu/~cest/news/inorgmetals.pdf+icp-oes+how+it+works&cd=1&hl= en&ct=clnk&gl=my

Truesdell, A. H. 1976. Chemical evidence of subsurface structure and flow in geothermal system. *Proceedings of the International Symposium on Water-Rock Interaction, Czechosslovakia*, 1974, 250-257.

Turcotte, D. L. and Schubert, G. 2002. *Geodynamics*. 2nd Edition. Cambridge University Press, Cambridge.

Vital Health Zone (2009). Silica - Minerals - Vital Health Zone. http://www.vitalhealthzone.com/nutrition/minerals/silica.html

Wakita, K. 1977. Analysis of hot spring water from Tawau and Semporna. Overseas Mineral Resources Development Sabah Berhad (Unpublished).

Wakita, K. 1977b. Analysis of hot water from Poring. Overseas Mineral Resources Development Sabah Berhad (Unpublished).

Wakita, K. 1978. Analysis of hot spring water from Andrassy and Sungai Balung. Overseas Mineral Resources Development Sabah Berhad (Unpublished).

Wakita, K. 1978b. Analysis of hot spring water from Andrassy, Sungai Balung, Sungai Jepun and Kg. Morok. Overseas Mineral Resources Development Sabah Berhad (Unpublished).

Water-Right Inc, 2009. DNR Grants Certification. http://www.cleanwatertesting.com/news_NR149.htm.

White, D. E. 1965. Saline waters of sedimentary rocks. American Association of Petroleum Geologist. Mem 4, 352-366.

White, D. E. 1970. Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources. *Geothermics*, Special Issue 2, 1, 58-80.

WHO (World Health Organization), 2006. Guidelines for drinking-water quality [electronic resource] : incorporating first addendum. Vol. 1, Recommendations. – 3rd ed. WHO Library Cataloguing-in-Publication Data.

Wong K.M. & Chan C.L., 1997. *Mount Kinabalu, Borneo's Magic Mountain*. Natural History Publications (Borneo) Sdn. Bhd. Kota Kinabalu.