THE RECOGNITION OF QUENCHED MAGMATIC GASES IN FUMAROLES AS A GEOTHERMAL EXPLORATION TOOL

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ABSTRACT

Magmatic and quenched magmatic gases in fumaroles can be identified by using a H_2S-H_2-CH_4 *ternary diagram even where* SO_2 *, HCl and HF have been scrubbed from the gases or have not been analysed for. Standard gas geothermometry is not applicable to such gases although high temperatures at depth are implied by their presence. However, fluids at depth in the immediate vicinity of fumaroles with this chemistry are likely to be acid or produce acid condensates and are not currently exploitable — although outlying convective parts of the same system may be exploitable. The diagram is also useful for identifying neutral reservoirs where overlying fumaroles are superheated, a feature occasionally mistaken as magmatic.*

Whilst most quenched magmatic gases have an "andesitic composition", often represented by their position on N_2-*He-Ar plots, they are not exclusive to it. Gases from neutral reservoirs can also have "andesitic" compositions, hence the* N_2-*He-Ar diagram should not be misused as an indicator of magmatic acidity at depth.*

1.0 INTRODUCTION

In geothermal systems developed in areas of high topographic relief, associated hot springs may be condensates or be located along outflows well away from any potentially exploitable reservoir (Bogie and Lawless, 1987) and be diluted by groundwaters, contaminated by condensates, and re-equilibrated. Therefore such waters may no longer provide any useful information regarding any potentially exploitable reservoir at depth. Thus fumaroles, if they occur, may provide the only information regarding the nature of any potentially exploitable geothermal reservoir in terms of temperature, enthalpy and acidity. The potential for magmatic acidity is usually evaluated by analysing for the magmatic volatiles: SO_2, HCl and HF. However, these highly reactive gases are not always found to be present in fumaroles associated with acid magmatic reservoirs, or are not always analysed for, particularly in historic analyses. The purpose of this paper is to provide a means of recognising fumaroles associated with reservoirs that contain acid magmatic volatiles, where these vent to the surface, and where SO_2, HCl and HF are either not detected or not reported.

Superheated fumarolic gases containing SO_2, HCl and HF are of clear acid-magmatic origin and are usually associated with volcanic centres with historic eruptions. These gases (and the others accompanying them) can be considered to be derived directly from a degassing magma body and imply high-temperature, vapour conditions at depth. They mark currently non-exploitable immature geothermal systems or non-exploitable parts of a larger system in terms of having a locally developed acid reservoir, high gas contents and possibly an unacceptably high level of volcanic risk. However, in the same systems there can also exist fumaroles without HCl, SO_2 and HF, but which, by association, obviously have an acid magmatic source. These fumaroles have lost the soluble, acidic gases as a result of condensation or interaction with groundwater near-surface. The existence of acid-chloride springs at slightly lower elevations can provide evidence for this. The fumaroles can be considered to have a "quenched magmatic" composition, and although they have lost their primary magmatic signature, they may still retain other distinctive chemical characteristics that distinguish them from those boiled off near-neutral reservoirs. The same type of "quenched magmatic" features may also be found without associated magmatic thermal activity, in which case recognition of their magmatic affinities is of considerable importance. It is also possible to find superheated fumaroles derived from near neutral geothermal reservoirs and these need to be clearly identified as such. This paper develops a technique for determining on the basis of H_2, H_2S and CH_4 relationship, whether a fumarole without SO_2, HCl, or HF, may in fact be directly associated with an acid magmatic system.

2.0 DATA COLLECTION

Data on fumarole chemistries have been compiled from the literature and from some projects that Kingston Morrison has worked on in Iran and Indonesia. These data are collated in Table 1. In order to minimise any variations resulting from differences in tectonic environments, only analyses of gases from fumaroles related to convergent plate margins are considered here. Some of the previously unpublished data is commercially sensitive and only the general location of the area from which the analysis was obtained is given. These analyses are all from separate fields and are representative compositions of high flow rate fumaroles, where samples have been obtained that have insignificant or no atmospheric contamination. O_2, N_2 and Ar analyses are provided to establish this. Similarly, analyses from the literature with indications of air contamination have not been included. Analyses in bold type are those from systems that are clearly magmatic as shown by the presence of HCl or SO_2. Where this is the case other indications of magmatic origins such as volcanic activity, supercritical fumarole temperatures, or acid-Cl crater lakes are also present. Despite the recognition that HF is commonly present as a magmatic volatile, very few analyses, particularly those with a full range of other gases, are available in the literature and HF has not been included in the table.

3.0 DISCUSSION

Table 1 shows that fumaroles with supercritical temperatures (>374°C) and hence of clear magmatic origin have distinct compositions. They contain SO_2 and HCl and have high H_2 concentrations, moderate concentrations of H_2S and low concentrations of CH_4. However, included in the data set are lower temperature fumaroles ranging in temperature from local boiling point to 115°C that also contain SO_2 and/or HCl, they also have low CH_4 concentrations, but differ by having high H_2S and low H_2 concentrations. These relationships can be best illustrated by a ternary diagram for H_2S, H_2 and CH_4 with appropriate weightings to spread the plots over the diagram. This is done in Figure 1 where the sample numbers (from Table 1) are shown and Figure 2 where the measured temperatures of the fumaroles are indicated. With the exception of one point (sample No 8 from Papandayan), all the analyses from fumaroles with supercritical temperatures plot in the H_2 corner'of the diagram. The gas compositions from lower temperature fumaroles that contain either SO_2 and/or HCI plot in the H_2S corner; as do a number of analyses where SO_2 or HCl are not reported. Some points plot along the H_2S-H_2 side of the diagram suggestive of a range between these two sets of compositions. One of these (8) is from a 400°C fumarole from Papandayan, while a 95°C fumarole from Papandayan (9) has a composition that plots in the H_2S corner of the diagram. The variation in composition of the magmatic gas samples, from H_2 rich at high temperature to H_2S rich at lower temperatures can be accounted for by the reaction:

$$SO_2 + 3H_2 \Leftrightarrow H_2S + 2H_2O \qquad (1)$$

(decreasing temperature →)

However, the proportion of H_2 to SO_2 in typical magmatic gases is insufficient to convert all the SO_2 to H_2S. As noted by Giggenbach (1987) additional H_2 can be produced from oxidation of Fe^{2+} in the rock matrix, but this reaction is apparently not fast enough to supply the necessary H_2 to maintain equilibrium in reaction (1). As a result there is often considerable SO_2 in lower temperature fumaroles and this is consumed primarily by the precipitation of native sulphur:

$$SO_2 + 2H_2S \Leftrightarrow 3S + 2H_2O \qquad (2)$$

(decreasing temperature →)

Table 1
Representative Fumarole Gas Analyses
(**Clearly** Magmatic **Fumaroles in Bold**)

No	Country	Area	Ref	S°	Temp	Xg	CO_2	H_2S	NH_3	He	H_2	O_2	Ar	N_2	CH_4	SO_2	HCl	Total Gas
					°C					mmol/mol dry gas								wt%
1	Cobrnbh	El Ruiz	j	-	82	0.0454	516	38.8	-	0.0037	1.90	-	0.005	58	0.01	436	1.30	5.7
2	Costa Rica	Miravales	h	-	98		983	9.0	-	0.0025	1.20	-	0.020	3.0	3.10	NR	NR	
3	Guatamala	Zunil	h	-	87		930	36.0	-	0.0045	6.44	-	0.200	25.0	1.30	NR	NR	
4	Guatamala	Tecuamburro	i	-	95	0.0440	835	130.9	-		0.02	0.000	0.150	33.6	0.09	NR	NR	9.3
5	Indonesia	Wayang Windu	c	n	93	0.0240	937	46.2	-	0.0060	1.02	-	0.014	14.7	0.65	NR	NR	5.4
6	Indonesia	Wayang Windu	c	n	94	0.0790	936	49.7	-	0.0050	0.51	-	0.014	13.4	0.19	NR	NR	15.9
7	Indonesia	Wayang Windu	c	n	91	0.0400	908	53.0	-	0.0100	0.26	-	0.100	38.5	0.05	NR	ND	8.7
8	Indonesia	Papandayan	j	y	400	0.0410	717	70.8	-		3.42	0.000	0.010	13.4	0.01	165	30.52	7.2
9	Indonesia	Papandayan	c	y	95	0.0400	594	399.0	-	0.0030	0.25	-	0.005	7.1	0.03	NR	NR	8.1
10	Indonesia	Sumatraa	e	n	98	0.0111	942	35.4	0.15	0.0031	10.6	0.000	0.011	11.8	0.09	NR	ND	2.6
11	Indonesia	Sumatra b	e	n	130	0.0021	886	83.6	3.91	0.0185	12.7	0.006	0.085	8.3	5.67	ND	ND	0.5
12	Indonesia	Sumatra c	e	n	97	0.0090	899	88.7	0.16	0.0060	3.30	0.000	0.023	8.3	0.83	NR	ND	2.1
13	Indonesia	Sumatra d	e	n	101	0.0223	964	17.0	0.03	0.0200	3.61	0.000	0.071	8.7	6.30	NR	ND	5.1
14	Indonesia	Sumatra e	e	y	105	0.0100	723	272.7	0.06	0.0085	0.014	0.006	0.024	3.9	0.28	ND	ND	2.2
15	Indonesia	Sumatra f	e	n	100	0.0093	843	141.0	0.02	0.0029	7.58	0.006	0.030	7.6	1.03	NR	NR	2.1
16	Indonesia	Sumatra g	e	n	94	0.0255	981	7.2	1.20	0.0056	1.36	0.000	0.012	6.9	2.14	NR	NR	5.8
17	Indonesia	Sumatra h	e	n	93	0.0053	941	23.8	-	0.0130	5.80	0.023	0.412	28.0	1.64	NR	NR	1.2
18	Indonesia	Darajat	e	n	118	0.0072	943	33.1	0.18	0.0293	12.3	0.000	0.068	11.2	0.35	NR	NR	1.7
19	Indonesia	Sumatra i	e	y	94	0.0160	761	234.0	0.03	0.0010	0.02	0.007	0.013	5.1	0.16	R	R	36
20	Indonesia	Sumatra j	e	y	112	0.0650	821	173.0	0.13	0.0050	0.01	0.017	0.008	61	0.03	NR	0.02	132
21	Indonesia	Sumatra k	e	y	95	0.0149	766	225.2	-	0.0090	0.10	0.005	0.187	7.0	1.28	NR	1.20	3.3
22	Indonesia	Merapi 78-3	f	y	820	0.0625	732	75.2	-		89.7	-	0.80	10.8	0.16	82	NR	11.0
23	Iran	Sabalan	d	n			942	480	-		0.01	-		10.0	0.04	NR	NR	
24	Japan	Showashinzan	j	y	336	0.0011	377	40.4	-		305	-	0.099	126	0.45	31	233.45	0.1
25	Japan	Mt Usu	j	y	690	0.0067	571	30.5	-		286	-	0.050	178	0.79	34	51.87	1.0
26	Mexico	Cerro Prieto	g	-	100		807	125	125		36.1	-	0.460	19.7	230	NR	NR	
27	New Zealand	Wairakei	h	n	104		975	7.0	-	0.0220	2.40	-	0.300	14.0	2.80	NR	NR	
28	New Zealand	Ngauruhoe	j	y	640	0.0399	402	170.3	-		66.1	-	0.053	426	0.01	255	62.60	5.2
29	New Zealand	Ketetahi	j	-	136	0.0417	906	31.2	-		24.4	-	0.012	12.9	25.64	0	0.00	8.8
30	New Zealand	White Is.	j	y	760	0.0720	735	34.0	-		42.0	-	0.007	2.9	0.14	113	71.98	11.8
31	New Zealand	White Is.	j	m	115	0.0250	820	150.0	-		0.60	-	0.070	10.2	8.90	5	3.20	5.5
32	Nicaragua	Momotombo	i	-			822	48.0	-		29.0	-		78.0	9.00	NR	NR	
33	Philippines	Mambucal	a	-	85	0.5370	970	7.0	-	0.0069	0.42	0.000	0.041	15.9	6.10	NR	NR	56.4
34	Philippines	Mt Apo	a	-	95	0.0055	957	15.0	-	0.0058	3.91	0.040	0.420	23.0	0.26	NR	NR	1.3
35	Philippines	Mt Pinatubo	a	-	98		898	92.0	-	0.0042	0.05	0.190	0.023	9.5	0.08	NR	NR	
36	Philippines	Biliran	b~		102	0.0340	888	99.0	-		0.10	-		6.3	0.20	R	0.90	7.4
37	Philippines	Tongonan	k	n	95	0.0139	944	42.1	-		5.78	0.000	0.067	5.8	2.70	NR	NR	3.2
38	Philippines	Mahanagdong	k	-	98	0.0969	989	6.1	-		0.49	0.000	0.005	2.1	1.84	NR	NR	19.1
39	Philippines	Alto Peak	l	n		0.0487	941	32.0	-		20.5	-	0.026	2.5	3.97	NR	NR	10.3
40	USA	Mt St Helens	j	y	540	0.0150	607	91.1	0.00		1622	0.000	0.051	31.2	0.01	48	59.16	2.5

NOTES

a) Giggenbach and Poreda (1993)
b) Lawless and Gonzales (1982)
c) Mandala Nusantara Ltd. (1997)
d) Khosrawi *et al.* (in prep)
e) Unpublished data.
f) Le Guern *et al.* (1982)
g) Nehring and D'Amore (1984)
h) Giggenbach (1987)
i) D'Amore and Panichi 1980.
j) Giggenbach (1990)
k) Salonga and Auman (1997).
l) Parilla Jr. *et al.* (1997)
m) Giggenbach (1982)

ref - source of data (see reference list)
S^0 - heavy sulfur depositing?
Xg - molar gas ratio (moles gas / moles H_2O)
NR - Not Reported
ND - Not Detected
R - Reported Qualitatively

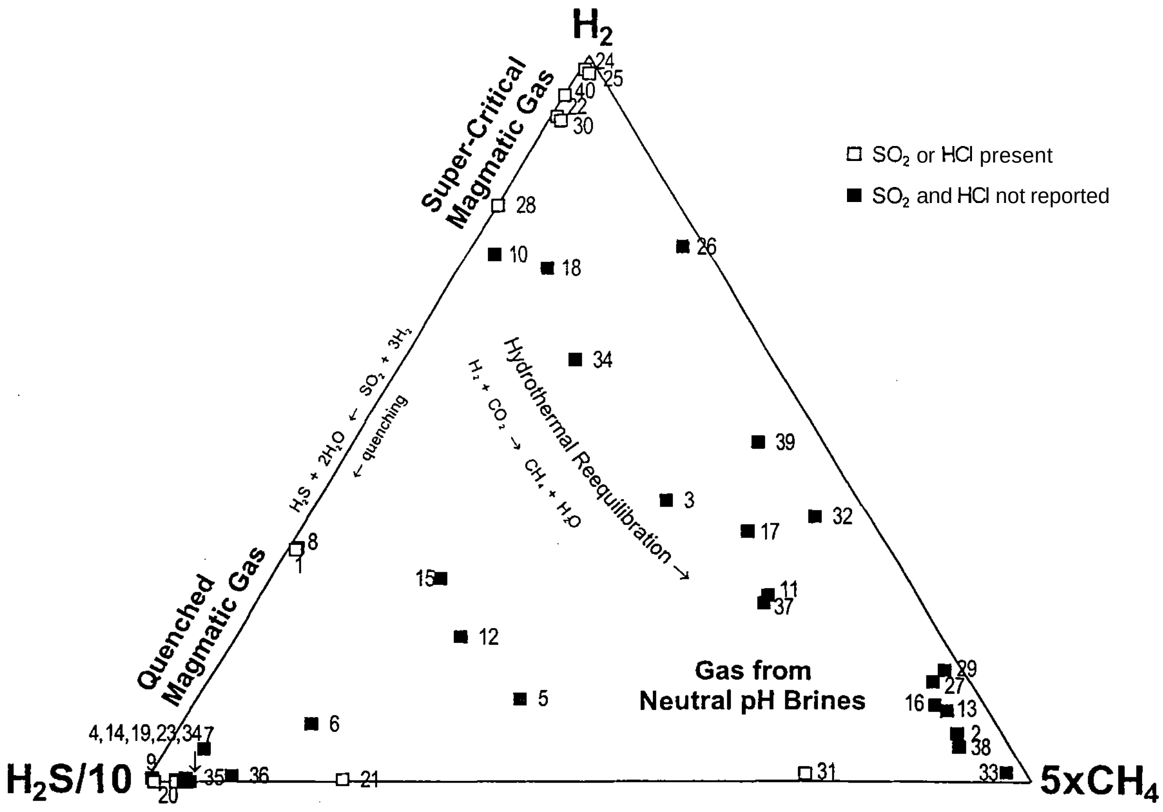

Figure 1
Relative H„ H,S and CH, contents of fumaroles (sample numbers from Table 1 shown)

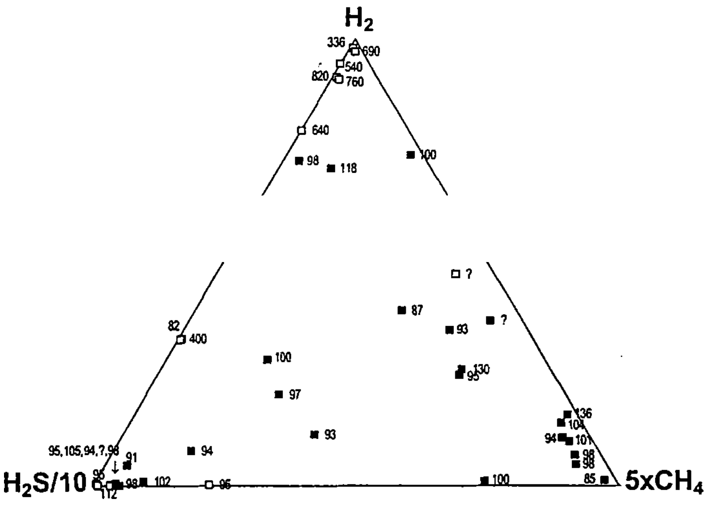

Figure 2
Relative H„ H,S and CH, contents of fumaroles with vent temperature (“C) shown

Equation (2) explains the abundance of sulphur (often in the form of solfatara chimneys) around fumaroles which produce magmatic gases. Sulphur also forms at the surface through the simple oxidation of H_2S in air but this is more common around weaker features where poorly dispersed gas mixes with air. Evidence that reaction (2) is occurring (and that SO_2 is present close to the surface) is provided by the observation of sulphur forming ***inside*** high-velocity solfatara vents, where O_2 is clearly absent. Even with these apparently magmatic features, HCl can be absent and SO_2 very low if reaction 2 is close to completion (eg. sample 14). Therefore, the observation of heavy sulphur deposition (in the absence of O_2) is evidence in itself of magmatic conditions at depth. If upflowing magmatic gases are quenched by condensation in ground water, HCl will be scrubbed out and SO_2 may be consumed by the following reaction, giving rise to acid-Cl-SO_4 waters.

$$4SO_2 + 4H_2O \Leftrightarrow 3H_2SO_4 + 2H_2S \qquad (3)$$

(decreasing temperature →)

These acidic waters may appear at high elevations close to the magmatic upflow. They can also be transported downslope through permeable lava flows, giving rise to high-flowrate, acid-Cl springs on the lower flanks of the volcano, displaced from the magmatic centre of the system. This may give a false impression of the extent of acidic conditions at depth. Regional hydrology and structural / lithological controls need to be carefully considered in assessing the distribution of acid fluids. Reaction (1) accounts for the generally low concentration of CH_4 in samples from magmatic fumarole. The concentration of CH_4 is controlled by the Fisher-Tropsch reaction:

$$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O\,, \qquad (4)$$

(decreasing temperature →)

If most of the H_2 is removed via reaction (1), as appears to be the case for most quenched magmatic samples, no new CH_4 can form from the above reaction. There are exceptions however, as shown by White Island sample (31) which plots towards the CH_4 corner of Figure 1. In this case it appears SO_2 has been scrubbed out on the periphery of the magmatic upflow, before equation (1) proceeds to completion, but at a sufficiently high temperature to allow generation of methane via equation (4). Similarly sample (21) also contains significant CH_4 but still has a distinctly low H_2 content and may also be being produced by this process.

Symonds and Gerlach (1998) modelled the quenching process by calculating the progressive mixing of a 915°C magmatic gas from the Merapi volcano with water. Although they did not include CH_4 in their calculations, they demonstrate the increase in H_2S and decrease in H_2 observed in the lower temperature fumaroles and the scrubbing out of HCl. Hence analyses with high H_2S, and very low CH_4 and H_2, but without reported SO_2 and HCl can also be considered to be quenched magmatic gases. Without this knowledge, quenched magmatic gas chemistry can present interpretative dilemmas, particularly when gas geothermometry is applied. The fumaroles may be physically impressive and located on apparently youthful volcanic centres, but the low H_2 concentrations can give anomalously low geothermometer temperatures — particularly using the H_2/Ar geothermometer of Giggenbach (1992). Another process by which a high proportion of H_2S and low H_2 and CH_4 can be obtained is by repeated boiling. Both H_2 and CH_4 are much less soluble than H_2S and are lost rapidly on initial boiling leaving some of the H_2S in solution. If such a water then moved laterally and boiled again it would produce a high proportion of H_2S in comparison to H_2 or CH_4. This is illustrated by the plots of samples 5 to 7 in Figure 1. They lie on a line indicative of progressive gas loss from solution and whilst H_2 and CH_4 concentrations are low they are not as low as that observed where there is other evidence for the gases being cooled magmatic gases. This is because some degree of re-equilibration to produce H_2 and CH_4 would occur during lateral movement which would also consume H_2S, see equation (4 and 5). Evidence of boiling and degassing is often seen in the low total gas contents of these features, in contrast to the relatively high gas contents in the magmatic fumaroles. Conversely if boiled-off gases are trapped in a steam zone, or the field is vapour dominated, the gases will re-equilibrate to the vapour phase and become H_2 rich and H_2S poor and plot towards the H_2 corner in Figure 1, for example sample (18) from Darajat.

Figure 1 *can* therefore be used to identify three groups of gases: primary magmatic gases, quenched magmatic gases and re-equilibrated gases. The fumaroles that have compositions that plot away from the H_2-H_2S and H_2S-CH_4 sides of the diagram come from fields that have been for the most part successfully exploited or by implication are viable prospects themselves, at least in terms of not containing magmatic gases with potential for producing acidity. *An* exception to this is Alto Peak (Reyes *et. al*, **1993)**, where the fumarole chemistry is indicative of a neutral reservoir and whilst a neutral reservoir was initially encountered, deeper drilling encountered acid magmatic volatiles. This is a result of the massive cold water influx from the surface being sufficient to quench the magmatic volatiles at depth, so there was re-equilibration of gases before they got to the surface, but not at sufficient depth to yield an exploitable system. Hence the absence of haroles with magmatic or quenched magmatic chemistry does not guarantee the absence of acid magmatic volatiles at depth, particularly where the field is in an area of high rain fall. However the main source of gases in exploitable fields will still be mainly primary magmatic, these gases have been cooled, neutralised and partially incorporated into hydrothermal mineral assemblages. Exploitable fields are those where this process is removed from the acid-magmatic centre in time or space. In terms of the species represented on Figure 1 the main process for this change in chemistry is deposition of pyrite where iron is derived from the country rock and the H_2S is derived from equations **(1)** and (3) according to:

$$Fe^{2+} + 2H_2S \quad \Leftrightarrow \quad FeS_2 + 2H_2 \qquad (4)$$

The H_2 released reacts with CO_2 to produce CH_4 thereby driving plots towards the CH_4 corner of the diagram, although as pointed out by Giggenbach **(1992)**, the Fisher-Tropsch reaction is very slow at temperatures less than about **250°C**. During this process gas equilibria are established which are those calibrated for gas geothermometers (D'Amore and Panichi, **1980** and Giggenbach, **1992)**. Therefore gas geothermometers should not be utilised on fumaroles that do not plot in the neutralised part of the diagram.

He and Ar are only reported for some of the analyses, these *can* be plotted on to the N_2-He-Ar plot of Giggenbach **(1987)** to establish **sources** for the gases (Figure 3). Analyses indicated to be "magmatic" on this diagram are those that either contain SO_2 or **HCl,** or plot in the same areas **as** those that do *on* Figure 1. **AS** would

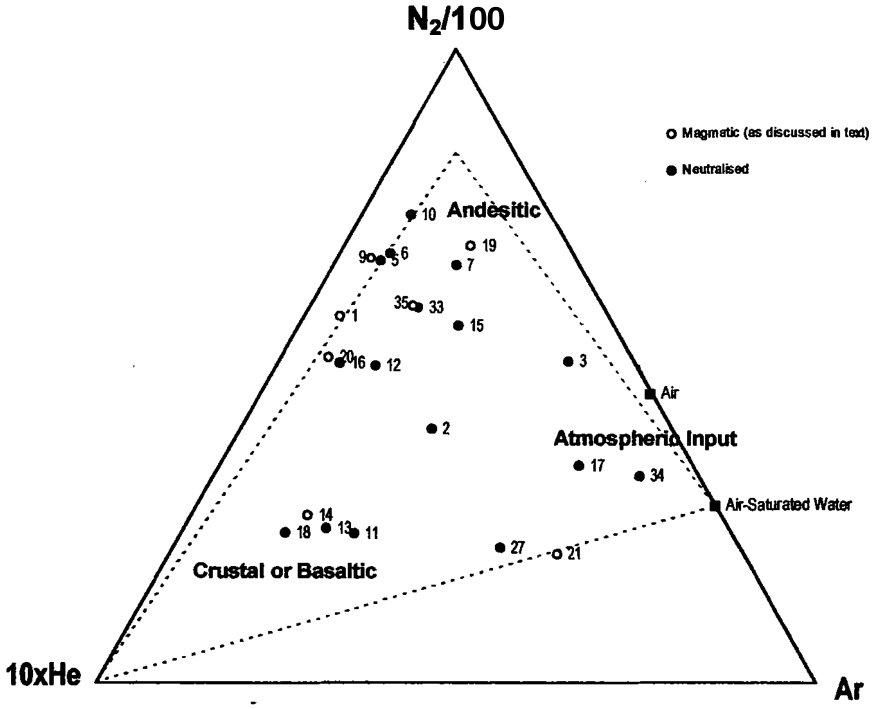

Figure 3. Relative N_2, H_2 and Ar contents of fumarole steam, with sample numbers shown (from Table 1)

be expected, the majority of analyses plot in the andesitic gas area, or on possible mixing lines with air saturated water. However, it must be remembered that N_2, He and Ar are highly conservative gases, with proportions that survive the neutralisation process described above. Therefore, whilst this diagram indicates source it is not indicating neutralisation and can not be used to discriminate acid reservoirs, nor did the progenitor of the diagram ever advocate this (Giggenbach 1992). A second group of analyses plots towards the basaltic *or* crustal input area, *or* on possible mixing lines with air saturated water. "Magmatic" samples are found within this group and the fact that a sample plots here also indicates nothing with regard to its degree of neutralisation.

Another property of fumaroles that is measured, but not always reported, is the total gas content, given as Xg in Table 1. The range of gas contents in each of the different groups of primary magmatic gases, quenched magmatic gases and re-equilibrated gases, overlaps such that the gas content can not be used to discriminate them. Neutralised gases have the widest range and the single highest value possibly reflecting lower temperatures and greater opportunity for condensation of steam. Consequently using fumarole gas contents to estimate reservoir gas contents can at best only a derive a maximum and high gas concentrations cannot be used as a predictor *of* acid conditions at depth. Within a single field however, it is important to look at the variation in total gas contents as this provides information about condensation and boiling processes, which in turn gives an indication of which data are most representative *of* the deep reservoir.

4.0 CONCLUSIONS

Magmatic fumarole steam that has been quenched and SO_2 and HCl removed (or not analysed) can be recognised by its high H_2S and low H_2 and CH_4 contents. Such a chemistry *can* be **best** recognised on a H_2S-H_2-CH_4 ternary plot. Standard gas geothermometers are not applicable to gases of this composition, although high temperatures are implied by the acid-magmatic associations. Deep fluids, including steam condensates, may be too acid to exploit in the immediate vicinity of such fumaroles. Therefore, recognition of fumarole gases with a quenched chemistry, and where other indications of acid conditions at depth are lacking, is useful in guiding exploration programmes away fiom potentially acid areas at depth. Neutral hydrothermal conditions may still exist beyond the zone of acid-magmatic conditions. The above technique provides a method of identifying acid-magmatic conditions *only* where suitable fumaroles exist. Whether magmatic vapours reach the surface with their magmatic signature intact will depend to a large degree on structural / lithological controls and shallow hydrology. So, the absence of magmatic volatiles at the surface does not guarantee finding a neutral resource. This method is useful for identifying gases fiom neutral reservoirs where they occur in superheated fumaroles, a feature occasionally mistakenly interpreted as magmatic. Such reservoirs contain neutralised magmatic gases the source of which *can* be established using Giggenbach's (1992) N_2-He-Ar diagram, however this indication of source does not indicate the degree of neutralisation and is not a useful predictor of acid conditions at depth.

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REFERENCES

Bogie, I and J.V. Lawless, 1987. Controls on the hydrology of large volcanically hosted geothermal **systems**: implications for exploration for epithermal mineral deposits. *Proc.* ***Pacific*** Rim ***Congress,*** 1987.

D'Amore, F. and **C.** Panichi, 1980. Evaluation of deep temperatures in hydrothermal *systems* by a new **gas** geothermometer. ***Geochim. Cosmochim. Acta,*** 4 : 549-556.

Giggenbach, W. F. 1982. The chemical and isotopic composition of gas discharges fiom New Zealand andesitic volcanoes. Bull. Volcanol., Vol. 45-3, 1982.

Giggenbach, W. F. 1987. Redox processes governing the chemistry of fumarolic gas discharges from White Island, New Zealand. Applied Geochemistry. Vol. 2, pp. 143-161, 1987.

Giggenbach, W. F. 1992. Chemical techniques in geothermal exploration. ***Application of geochemistry in geothermal reservoir development, D'Amore (Ed), UNITAR, Pisa:*** 119-144.

Giggenbach, W. F. 1990. The chemistry of fumarolic vapor and thermal-spring discharges from the Nevado del Ruiz volcanic-magmatic-hydrothermal system, Colombia. *J. Volc. Geotherm. Res,* 42: 13-39.

Giggenbach, W. F. and RJ. Poreda, 1993. Helium isotopic and chemical composition of gases from volcanic-hydrothermal sytems in the Philippines. *Geothermics* Vol. 22: 349-350.

Khosrawi, K., B. Talebi, I. Bogie, and P.R. Barnett, In prep. *An* exploration model for the Sabalan geothermal prospect, Islamic Republic of Iran.. In prep for GRC2000.

Lawless, J. V. and RC. Gonzales, 1982. Geothermal geology and review of exploration, Biliran Island. ***Proceedings of Pacific geothermal conference:*** 161-167.

Le Guern, F., T.M. Gerlach, and A. Nohl, 1982. Field gas chromatograph analyses fiom a glowing dome at Merapi Volcano, Java, Indonesia, 1977,1978,,1979. *J.* Volc. ***Geotherm. Res,*** 14: 223-246.

Mahon, W. A. J. and G.D. McDowell, 1977. Magmatic-volcanic steam, its role in geothermal areas. ***DSIR Bull.*** 218: 11-18.

Mandala Nusantara Ltd. 1997. Notice of resource confirmation, Wayang Windu geothermal field, West Java, Indonesia.

Parilla Jr., E. V., M.M. Martinez, and N.D. Salonga, 1997. Assesment of fluid acidity in Alto Peak and Mahanagdong geothermal fields, Leyte, Philippines. ***Proceedings 18th PNOC-EDC Geothermal Conference:*** 182-188.

Reyes, A. G., W.F. Giggenbach, J.R.M. Salera, N.D. Salonga, and M.C. Vergara, 1993. Petrology and geochemistry of Alto Peak, a vapor-cored hydrothermal system, Leyte Province, Philippines. Geothermics 22:479-520.

Salonga, N. D. and RO, Auman, 1997. *Gas* equilibria in Tongonan, Mahanagdong and Alto Peak geothermal fields. ***Proceedings 18th PNOC-EDC Geothermal Conference:*** 156-165.

Symonds, R B., and T.M. Gerlach, 1998. Modeling of the interaction of magmatic gases with water at active volcanoes. ***Water-RockInteraction, Arehart & Hulston (eds), Balkema, Rotterdam:*** 495-498.