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CONDUCTING SOIL GAS SURVEYS OF NEW ZEALAND GEOTHERMAL AREAS WITH A PORTABLE MASS SPECTROMETER

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SUMMARY - An investigation into the feasibility of conducting soil gas surveys with a portable quadrapole mass spectrometer connected directly to the sample hole. The study site in the Tauhara Geothermal Field covered hot and cold ground along a 120m line. The results are presented in a semi-quantitative format as bar graphs for CO_2, H_2S, CH_4, He and Ar plus two unusual gases for geothermal areas, COS and C_6H_6. The suitabiltiy of the mass analyser for this type of field work are discussed along with its wide dynamic range and multi-gas detection capability. Also discussed is how the method can illustrate the difference between conductively and convectively heated ground. A suggested future application, searching for buried faults in geothermal areas, is discussed briefly.

1. INTRODUCTION

Understanding a complex system from a chemical perspective usually involves the collection of samples for the analysis of one or more of the components that make-up the system. When the system is accessible, obtaining the required samples is usually a straight-forward procedure. For geological systems, such as buried ore bodies and oil, gas or geothermal reservoirs, direct sample collection is not possible. A drill hole into the system can provide the necessary samples, but at a considerable cost that increases in proportion to the depth of the system. It is therefore more cost effective to conduct preliminary studies at the surface using indirect means, such as the geophysical methods developed for geothermal areas (i.e., resistivity measurements, heat flow studies and magnetic and gravity surveys).

Indirect chemical methods for the preliminary assessment of a geothermal system have required the presence of surface features, such as fumaroles and hot springs, to provide water and steam samples for chemical analysis. Soil gas surveys are a relatively new technique that offer a means of collecting geothermal chemical data when there are no surface emanations or wells, and can provide supplementary data when surface features are present. The method is based on the detection of concentration anomalies in gases or volatiles collected at the surface over a suspected ore body or energy resource. One or more gases that can be related to the deeper system (eg., reactions between ore bodies and the surrounding rock environment or degassing due to boiling in a geothermal resemoir) are chosen for the survey. Soil gas techniques, developed in the 70's and 80's for mineral exploration (McCarthy & Reimer, 1986 review), have been applied with some success to the study of geothermal systems over a number of years in several countries, including New Zealand. Some surveys have concentrated on a single species, such as Hg vapour (*Noda*, 1981) or radon (Whitehead, 1984), but most look at several species (Hg, CO_2 and Rn, Koga, et al., 1982; Hg and CO_2, Sheppard, et al., 1988; He, H_2, CO_2, CH_4 and Rn, Bertrami, et al., 1990; He, CO_2, O_2, and N_2, Hinkle, 1991; CO_2, H_2S, CH_4, "air" and H_2O vapour, Finlayson, 1992b). A similar technique called "geogas", looks not at gases migrating from a deep system, but at the ultra-trace quantities of particulates carried to the surface by these gases, and provides an indication of the relative quantities of heavy metals, and such non-metals as Si, S, Cl and As, present at depth (Christenson, et al., 1988).

The sampling of soil gases may employ direct collection or static collection, usually at depths of one half to one metre, by one of several techniques which are used separately or in combination. Collecting samples at one metre has the advantage of excluding most of the meteorological effects that influence more shallow samples. Static sampling employs a gas-specific absorbent placed in the ground for a period of time before it is returned to the laboratory for analysis. Examples of absorbers that have been used in geothermal soil gas studies include molecular sieves for CS_2 and COS (Hinkle and Harms, 1978), gold wire for Hg (*Noda*, 1981), and activated charcoal for hydrocarbon gases (Klusman and Voorhees, 1983, Noda, et al., 1992). Radon may be analysed on site at the time of collection (Noda, et al., 1982; Baubron, et al., 1991) or detected by means of a film absorber left in the ground, which is preferred by some investigators as it provides an integrated signal (Whitehead, 1984). Soil itself acts as natural gas absorbent and may be collected and analysed for absorbed gases or volatiles. Mercury surveys are often based on this method (Koga, et al., 1982; Prijanto, 1986; Sheppard, et al., 1990) and Nicholson, et al. (1989) reported on the use of soil-absorbed NH_3 as an exploration tool for low-enthalpy geothermal systems.

The third soil gas technique, direct collection, in which gas is extracted from the pore space of soil by pumping, requires a sealed hole, preferably one half to one metre deep. The hole can be drilled by hand and fitted with a pipe or hollow sampling probe which is sealed around its outer circumference. Alternatively, a steel probe can be driven into the ground with a sledge hammer, although it can be difficult in some soils to reach a depth of one metre and even more difficult to remove the probe. The direct method is better suited for gases that are non-condensable at ambient temperature and pressure (He, Ar, CO_2, CH_4, H_2S, etc.) rather than for volatile constituents such as Hg. Analysis can be done on site or the gas can be collected in evacuated containers for later, laboratory analysis. Direct collection into evacuated containers for laboratory analysis of CO_2, CH_4, H_2, and He was used by Bertrami, et al. (1990) in a study of several Italian geothermal areas, and Hinkle (1991) used similar techniques to monitor He, CO_2, O, and N_2 in soil gases from the Roosevelt Springs geothemal field in the U.S.A.

While laboratory analysis has several advantages (eg., concentration of field time on sample collection; the convenience of a more stable environment; access to larger, more sensitive analysers), field analysis allows better management of the soil gas survey. It is a major advantage, for example, to know that a sample from a particular site is "good" (e.g. consecutive runs give the same analysis); if not it can easily be repeated under the same sampling and weather conditions.

A number of analytical instruments have been used for field analysis of soil gases in geothermal and volcanic areas, including scintillation counters for Rn (Koga, et al., 1982; Baubron, et al., 1991), infra-red spectrometers for CO, (Sheppard, et al., 1990; Baubron, et al., 1991), gas chromatographs for inorganic gases and simple hydrocarbon gases (Sheppard, et al., 1990; Finlayson, 1992b), leak detector mass spectrometer for He (Baubron, et al., 1991), and quadrapole mass spectrometers for all gases and vapours with a mass of 100 or less (Baubron, et al., 1991). Each method has advantages depending on the application, such as sensitivity and specificity (scintillation counters; He leak detectors) or multi-gas detection per sample (gas chromatography; mass spectrometry).

This paper describes an investigation into the feasibility of using a portable quadrapole mass spectrometer for direct on site analysis of soil gases in geothermal areas. The unique feature of this study is the direct connection of the mass analyser to the sampling probe, whereby the interstitial soil gases are pumped directly to the inlet of the mass spectrometer, using only an ice-water cooled trap to reduce the amount of water vapour reaching the instrument (especially necessary when holes drilled in the hottest ground became steam fumaroles !).

2. STUDY AREA

The site selected for this work lies within the Tauhara Geothermal Field, which is situated along the north-eastern border of the town of Taupo in the centre of the Taupo Volcanic Zone of New Zealand's North Island (Figure 1). The regional and surficial geology and the local hydrology of Taupo and the Tauhara field have been summarised by Henley and Stewart (1983). The important features for this study are the highly permeable and porous pumice breccias that make up the surface layers in this region and overlie the high permeability Wairakei Lapilli Tuff Group. This latter formation is believed to contain the shallow hot water aquifer (at a depth of approx. 70m) tapped by most of Taupo's domestic hot water wells. The survey area, part of a paddock for sheep and cattle, is directly east of the back fence of the Taupo Golf Club's Centennial course and approximately 200 metres SW of TH1, one of the deep exploration wells drilled in the Tauhara field in the mid-1960's. It was chosen for ease of access, close proximity to the Wairakei Research Centre (13km) and because the site was used by geophysicist colleagues for a ground temperature survey from 1989 to 1991 (Mongillo, pers. communication, 1992). In that study, ground temperatures were measured from the surface to a depth of one metre along a line running in an east-NE direction from the golf course fence for approximately 120 metres. The temperature transect started in "cold", grass-covered ground, and proceeded through gradually increasing soil temperatures towards a patch of hot, faintly steaming ground, bare of any vegetation. We believed that a soil gas survey line parallel to the temperature transect and encompassing the same temperature extremes would provide an excellent test of the gas probe-mass spectrometer system. For our purposes, we selected a spacing of 10-metres between sampling holes, starting the first hole (TH-1) approximately 10 metres from the golf course boundary and proceeded east-NE to the final hole (TH-12) just past the furthest boundary of the hot patch of ground (Figure 1).

3. EXPERIMENTAL

Gas samples were collected from a 1 metre deep hole which had been drilled with a hand auger. A probe was inserted into the holes and pumped to remove atmospheric gases before connecting it to the mass spectrometer via tubing and an ice-water cooled water vapour trap. The design and operation of the probe, which was built for an earlier soil gas survey, is described by Finlayson, 1992a). The temperatures at the bottom of each hole (downhole temperature) and at the surface (air temperature at ground level) were measured with a 1.5m K-type (chromel/alumel) probe and a Fluke 52 Series digital thermometer. Atmospheric pressure was not recorded because the survey (with the exception of the first hole, TH-1/92) was completed in one day. TH-1/92 was drilled on the previous day, but further work on that day was not possible as the hand auger broke while drilling that hole.

The mass analysing system used for this study was designed and assembled by one of the authors (J. Patterson) and was also operated by him during the field work. The mass spectrometer was a Dycor Quadrapole Gas Analyzer, Model

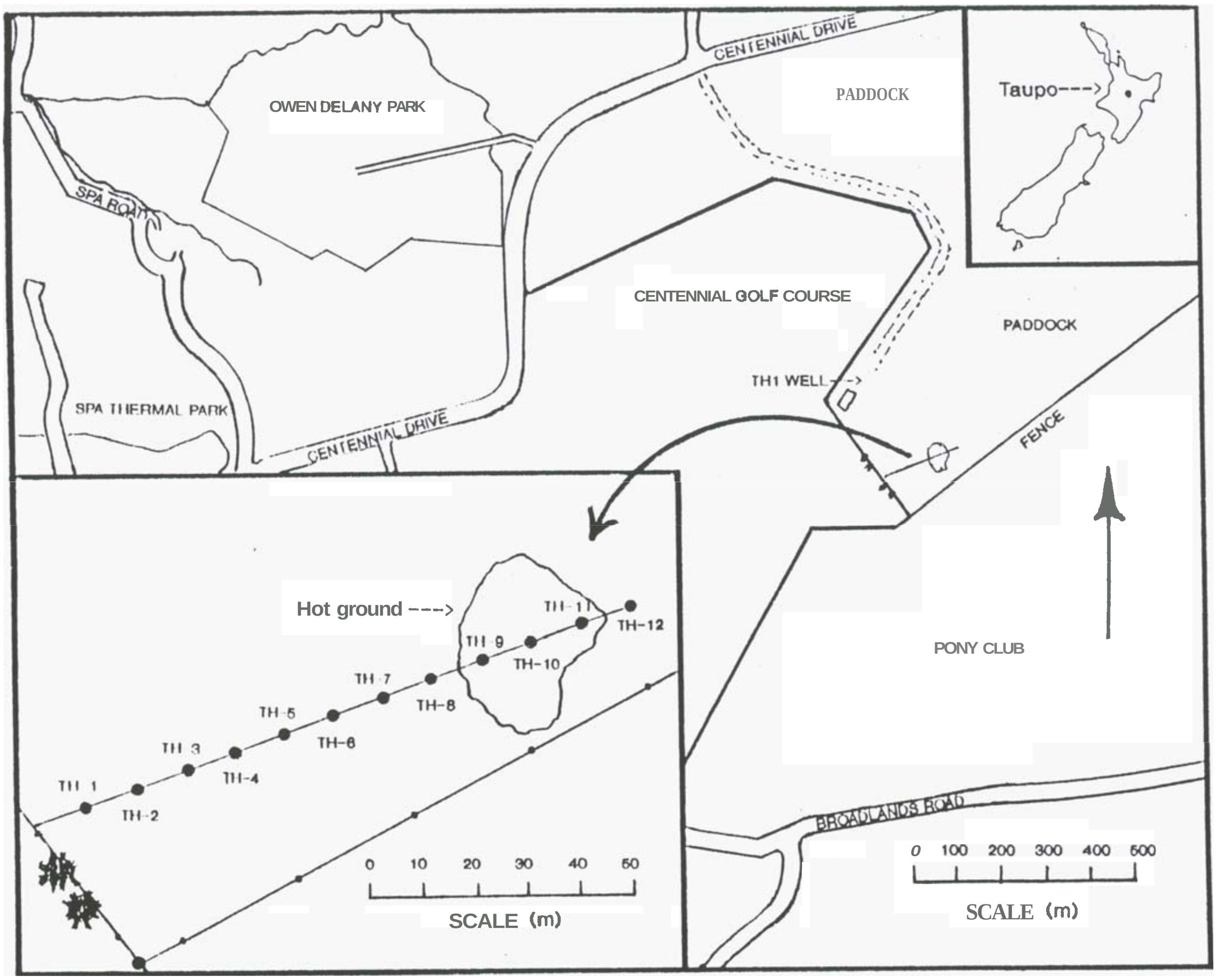

Figure I- Location map of Tauhara soil gas survey line with sample sites indicated

MA100M with a nominal mass range from 1 to 100 daltons (actual range was 1 to 150 daltons). After an initial, rough pump down in the laboratory, the working vacuum was maintained while travelling and in the field by a Varian 30 litre/second triode Vacion pump. Two power supplies were used to operate this ion pump, a small 6 kV supply for travelling and a more powerful high voltage supply for the field work. Four, linked Portalac 40 amp-hour lead acid batteries supplied the electrical current to run the pump supplies and the mass spectrometer via an Ebbet Automation 12 volt DC to 220 volt AC inverter. The batteries were capable of powering the system for approximately 8 hours of field work before requiring an overnight recharge.

The sample train from the sample probe to the mass spectrometer is shown in Figure 2. Filtering was provided by an ice-water cooled trap for water vapour and by a Nupro 0.5 micron filter to protect the inlet valves and membrane. The inlet to the mass spectrometer consisted of a silcone membrane backed by a stainless steel frit. The middle arm of a stainless steel tee was attached to the membrane inlet so that sample gas could be flowed past the inlet by means of a small battery-powered pump. Two stainless steel valves were used to isolate the membrane inlet from the sampling train. The sampling pump was operated with a speed controller so the sample train could be flushed-out quickly and then, with the mass spectrometer inlet open, pumped for sampling at a low speed (approx. 100 ml/min).

The mass spectrometer was operated by a laptop computer (Toshiba 1200) using MASSPORT software developed by Patterson. In addition to turning the instrument on and off, the computer was used to start a run by scanning through a mass range entered into the computer (usually 1 to 100 daltons). After about 30 to 40 seconds, the results would be displayed on the computer screen as a mass spectrum of the gases from the hole being sampled. Two runs were made at each site and, in the majority of cases, produced identical mass spectra. Occasionally additional runs were required before successive runs produced identical spectra and the probe-analyser system could be moved to the next hole. The computer also contained software to convert the mass spectrum data for a particular gas species (or mass number) into a bar graph or other suitable format for each hole sampled up to that point.

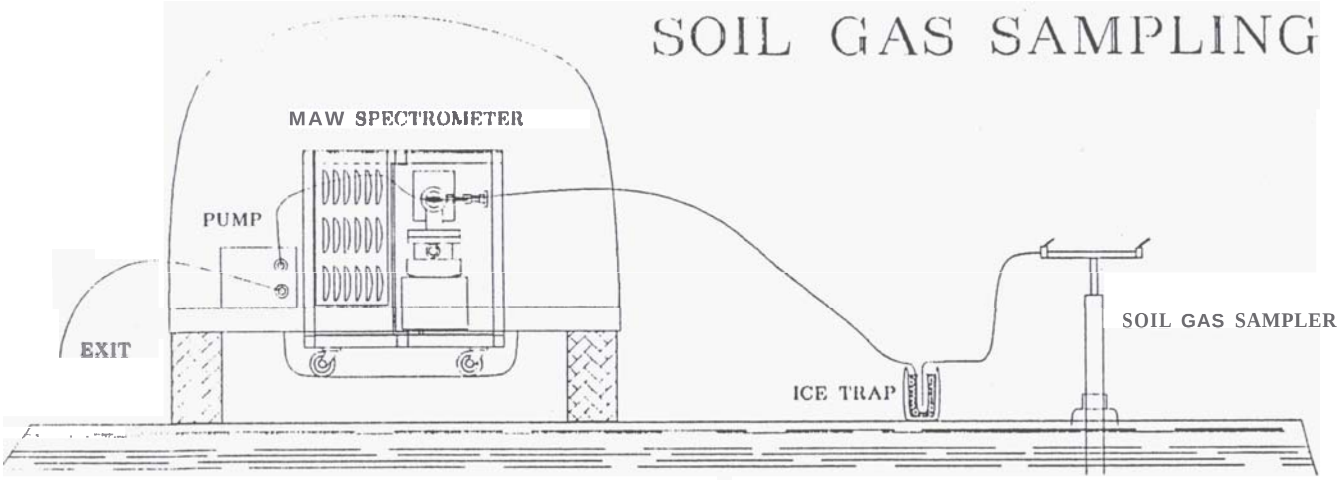

Figure 2. Schematic diagram of sample probe and vehicle-mounted quadrapole mass spectrometer

For transportation and use in the field, the mass spectrometer was secured in the rear of a station wagon with a cargo strap and the batteries were stored in two wooden boxes that fitted on the floor behind the passenger seat. The large ion pump power supply was mounted in a third wooden case and secured next to the spectrometer. Other smaller item such as tubing, cables, tools and test instruments were stored in a fourth box.

4. RESULTS

Because our purpose was to determine the feasibility soil gas analysis at the point of collection, we did not calibrate the mass spectrometer and reduce our data to quantitative values. It was sufficient to present the data in a way that would portray the relative changes in gas levels for a particular species between each sample point along the survey line. Figure 3 shows the results as bar graphs, where the height of the bar represents the partial pressure of that particular species in the mass spectrometer and the points on the x-axis are the numbers of the sample holes. For clarity, the "TH-" designation of the sample hole numbers was not used in these plots. In most cases, additional bars have been plotted which represent lighter ion fragments split from the principal mass of a particular gas (eg., 28 m/z, CO^+; 16m/z, O^+; and 12m/z, C^+ from 44m/z, CO_2). The gases plotted in Figure 3 are the usual gases associated with geothermal systems in New Zealand (CO_2, H_2S, CH_4, He, and Ar) plus some unusual species that appeared to be present at some sites, although at very low levels (carbonyl sulphide, COS and benzene, C_6H_6). Hole number 2 does not appear on the graphs because it was never drilled owing to failing daylight and a lack of time to return the following day to complete it.

The downhole temperature at each site has been plotted as a line graph on each of the bar graph plots in Figure 3 so that correlations between temperature and gas levels are more apparent. Air temperature at ground level was also measured at or nearby each site and these temperatures reflect the time of day more than anything else, with a low of 11°C in the morning and a high of 16°C in the late afternoon, Table 1 shows the analyses in mole % of three duplicate gas samples taken from TH-9 at a later date and analysed by gas chromatography and titrimetry in the laboratory. These results are provided to give the reader an indication of the actual concentration of the conventional gases present in the soil gases from the patch of hot ground (TH-9, -10, and -11).

5. DISCUSSION

5.1 Mass Spectrometer Performance

The mass spectrometer used in this investigation was originally set up in a laboratory environment to monitor, among other things, hydrocarbon gases generated by catalysis studies. Although it was necessary to convert the instrument to a portable, battery-operated mode for the soil gas work, the necessary equipment and design for this were already in place. The resulting portable system, however, had not been field tested and had not travelled more than a few kilometres from its home base near Wellington. It easily passed the first test of this study, a 400km highway drive to Wairakei and a short, but very bumpy drive across a paddock to the field site with no apparent affect on the operation of the mass spectrometer. It was also apparent at the end of this study, that the four 40 amp-hour 12 volt batteries were sufficient to operate the analyser system for a reasonable period in the field (approximately 8 hours), providing that access to an AC power line was available shortly afterward far an overnight recharge of the batteries.

Of greater concern was the effect the sample gases might have on the mass spectrometer, especially with regard to its operation and to corrosion. Before going to the field site, the system was tested on the lawn outside the Wairakei laboratory. In this trial the ice-water trap was not used and it is believed that this resulted in water vapour entering the inlet. This was beleived to be the cause of the ion pump shutting down with the near loss of the working vacuum. The vacuum was recovered and the ice trap was made a permanent fixture of the sample train. No obvious evidence of corrosion was found at the conclusion of this work, but

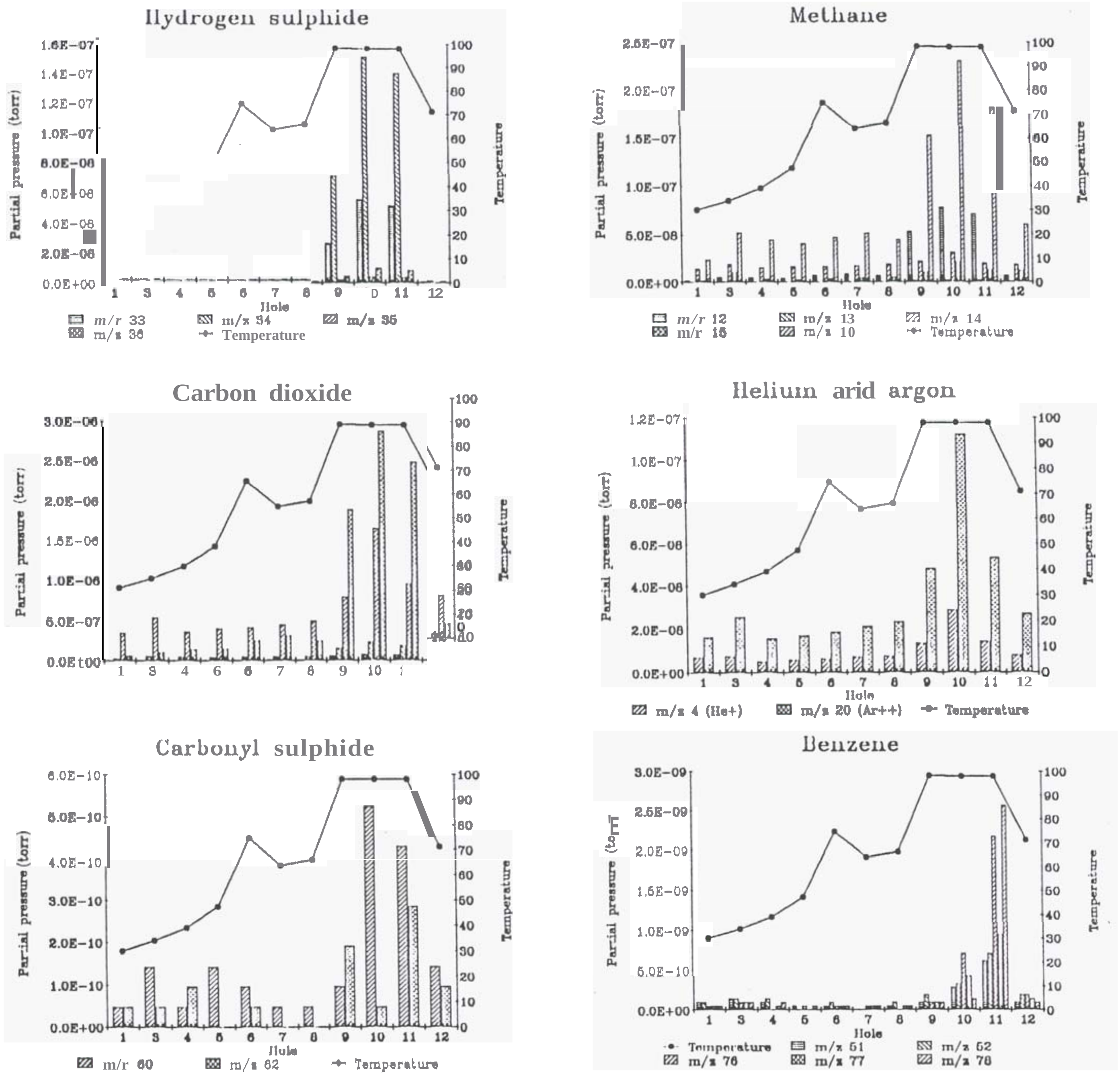

Figure 3- Bar graph plots for six soil gases measured on the Tauhara survey line. The downhole temperatures line graph has been plotted on each bar graph.

Table 1- Analysis of three gas samples from TH-9

	Mole %			
Gas	7010-2-N	7010-3-N	7010-4-N	Average
CO_2	92.6	92.9	92.8	92.8
H_2S	3.98	3.81	3.80	3.86
He	0.00040	0.00026	0.00023	0.00030
H_2	0.60	0.62	0.60	0.61
O_2	0.0091	0.0093	0.033	0.017
N_2	1.31	1.17	1.29	1.26
CH_4	1.47	1.50	1.42	1.46
Ar	0.011	0.0092	0.011	0.010
Total	99.98	100.01	99.95	100.02

there were signs of some very minor corrosion products in the inlet system when this equipment was later used for a more extensive survey in the Rotorua geothermal field. Overall, the mass analyser system operated very well, with no serious problems, even when the three 98°C holes (TH-9, -10, and -11) were sampled. These three holes became steam fumaroles as soon as the hand auger was removed from the hole, which required careful monitoring of the ice-water trap to add more ice to prevent water vapour overload.

5.2 Tauhara Survey Line

The survey site chosen provided a range of soil gas concentraions from low levels of what are probably not geothermal gases (TH-1 and TH-3) at the "cold" west-SW end (downhole temperature approx. 30°C) to high concentrations of geothermal gases (TH-9, TH-10, and TH-11) at the "hot" east-NE end of the line (downhole temperature approx. 98°C). In between these extremes the downhole temperature rises gradually, except for a 75 degree spike at TH-6 and then a final rise to boiling at TH-9. This same pattern was also observed in the ground temperature study conducted at the same site in 1989-1991 (M. Mongillo, pers. communications, 1992).

Between the hot and cold ends of the survey line, gas levels do not reflect the gradual temperature rise or the temperature spike at TH-6. Instead the levels remain relatively constant with the exception of a small bump at TH-3. This behaviour can be related to the mechanisms for heat discharge through soils in thermal ground. According to *Allis* (1979), conductive heat flow becomes dominant below 60°C and convective heat flow above 80°C with a transition zone between 60° and 80". The patch of hot ground covered by the east-SE end of the soil *gas* line (TH-9, -10, and -11) represents convective heat flow resulting from a high steam and gas flux through highly permeable soil. Holes TH-1 to TH-8 are in ground dominated by conductive heat transfer between adjacent soil particles and the steam and gas flux from the underlying, shallow aquifer has become negligible. Soil gases in this area would be controlled by surface and near surface conditions and are probably a mixture of atmospheric and biogenic gases with the former being dominant. Any geothermal component would only be present at very low levels. The graphs for CO_2 and He in Figure 3 support this conclusion. Mass number 44, which represents CO_2, just about disappears in this region so the most abundant mass number 28, which can be the CO_2 ion fragment CO^+ or N_2, must therefore be N_2. Helium, which is often used as a soil gas tracer for geothermal systems (Hinkle, 1991) remains at a nearly flat level in this conductive heat region, showing an increasing concentration only in the hot spot area. There is no clear cut transitional zone on this survey line, although TH-12 may be located in such a zone. More holes with a closer spacing than 10 metres might reveal a transitional zone.

The presence of COS and benzene are hard to explain from a geothermal context, but were included here to illustrate the wide range of gas concentrations as well as gas species that the mass spectrometer *can* detect. The most abundant gas detected in the samples, CO_2, was four orders of magnitude (10,000 times!) more abundant than these two gases. We could also have included other gases at similar levels, such as CS, and SO,, as there were mass peaks corresponding to their mass numbers on spectra from some of the sites. There is some precedence for including COS and CS, as these gases were the basis of a soil gas survey in the Roosevelt Hot Springs area of **Utah, USA,** conducted by Hinkle and Harms (1978). Although the benzene graph shows a relatively large peak in the hot ground area, it may not be related to gas migrating from the depths as much as some remnant from one of the more usual occupants of the sample site paddock that is slowing cooking away.

6. CONCLUSIONS

This investigation has shown that the portable quadrapole mass spectrometer is a suitable instrument for field use in soil gas surveys and with care *can* be directly connected to a sample hole for "real-time" analysis. Used in this was its main advantage is better management of the survey; it lets you see where you've been and where you are going. It also proved to be not as fragile an instrument as might have been expected and stood up well to the rigors of field work.

As would be expected, carrying-out the field work resulted in a number of ideas for improvements to the equipment. One draw back with the mass analyser system is the need for a vehicle to transport it to the survey site and to move it along the survey line, restricting surveys to vehicle accessible sites. If the mass spectrometer, power supply and batteries were available in smaller and lighter versions, back-packing the equipment to less accessible sites might be possible. With the presenst system, between 10 and 15 holes could be drilled and sampled in one day. The most time consuming tasks were hand-drilling the hole and waiting for thermometer probe to equilibrate with the downhole soil temperature. A small petrol driven auger (no bigger than a small chain saw) would *speed* up the drilling. Overcoming the temperature probe lag time might be more difficult. On a subsequent survey, we had four temperature probes and tried to keep 3 drilled-holes ahead of the working hole *so* temperature probes could be equilibrating in these holes. Equilibration could also be speeded-up if the probe were sheathed with a thinner and better heat conducting material than the fibre glass cladding used in this study.

The analysis in "real-time" capability of this sample probe-mass spectrometer system suggested that this would be a *good* system to use in a search for buried faults in geothermal areas, especially when there were no surface indications of the faulting. The resulting plots of soil *gas* levels along a survey transect perpendicular to the suspected fault line might look similar to the graphs in Figure 3, although the "fault *gas*" spikes would not be expected to be of as great a magnitude as levels reached over the hot ground. As the **Rotorua** Geothermal Field has a number of suspected buried fault systems and funds were available for some additional soil gas work, a search for Rotorua faults has begun and the results will be reported at a later date.

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8. REFERENCES

Allis, R.G. **(1979).** ***Heatflow and temperature investigations in thermal ground.*** Geophysics Division **Report No. 135,** Geophysics Division, DSIR, Wellington, New Zealand.

Baubron, J.-C., Allard, P., Sabroux, J.-C., Tedesco, D., and Toutain, J.-P. **(1991).** **Soil gas** emanations **as precursory** indicators of volcanic eruptions. ***Jnl. Geological Soc., London,*** Vol. **148, 571-576.**

Bertrami, R., Buonasorte, G., Ceccarelli, A., Lombardi, **S.,** Pieri, **S.,** and Scandiffio, G. **(1990).** **Soil** gases in geothermal prospecting: Two case histories (Sabatini Volcanoes and Alban Hills, Latium, Central Italy). ***Jnl. Geophys. Res.,*** Vol **95(B13), 21,475-21,481.**

Christenson, B.W., Malmqvist, L., Kristiansson, **K.** and Finlayson, J.B. **(1988).** **Soil gas** trace metal **transport** - the Geogas method applied to NZ epithermal and geothermal environments. In: ***Proceedings of the 4th New Zealand Geothermal Workshop, 1988,*** **pp. 155-160.**

Finlayson, J.B. **(1992a).** ***The 1990 soil gas survey over the Rotorua Geothermal Field, Rotorua, New Zealand.*** DSIR Chemistry Report No CD **2417,** DSIR Chemistry, Petone, New Zealand.

Finlayson, J.B. (1992b). A **soil** gas survey over **Rotorua** Geothermal Field, Rotorua, New Zealand. *Geothermics*, Vol. **21(1/2), 181-195.**

Henley, R.W. and Stewart, **M.K. (1983).** Chemical and isotopic changes in the hydrology of the Tauahara Geothermal Field **due to** exploitation at Wairakei. ***Jnl*** Volcanol. ***Geotherm. Res.,*** Vol **15(4), 285-314.**

Hinkle, M.E. and Harms, T.F. **(1978).** CS_2 and COS in **soil gases** of the Roosevelt Hot **Springs** Known Geothermal Resource ***Area,*** Beaver County, **Utah.** ***Jnl. Res. US Geol. Survey,*** Vol. 6(5), 571-578.

Hinkle, **M.E. (1991).** **Seasonal** and geothermal production variations in concentrations of He and CO_2 in **soil** gases, Roosevelt Hot Springs Known Geothermal Resource Area, **Utah, U.S.A.** ***Applied Geochem.,*** Vol. **6(1), 35-47.**

Klusman, R.W. and Voorhees, **K.J. (1983).** A new development in petroleum exploration technology. ***The Mines Magazine,*** **Vol.73, 6-10.**

Koga, A., Taguchi, **S.** and Mahon, A.J. **(1982).** The **use** of volatile constituents in geothermal fluids for assessing the type, potential and **near** surface permeability of a goethermal system: The Broadlands Geothermal *Area,* N. Z. In: ***Proceedings of the Pacific Geothermal Conference & 4th New Zealand Geothermal Workshop, 1982,*** **pp. 135-138.**

McCarthy Jr., J.H. and Reimer, G.M. **(1986).** Advances in soil **gas** geochemical exploration for natural resources: Some current examples and practices. Jnl. ***Geophys. Res.,*** Vol. **91(B12), 12,327 - 12,338.**

Nicholson, K., Franklyn, **A.K. and Aredes, S.delV. (1989).** Geochemical soil surveys: *An* exploration technique for low-enthalpy goethermal resources. In: ***Proceedings of the 11th New Zealand Geothermal Workshop, 1989,*** pp. **189-193.**

Noda, **T. (1981).** Volatile mercury capture with **a** gold needle and its application to geothermal prospecting. In: ***Proceedings of the 3rd New Zealand Geothermal Workshop, 1981,*** pp. **225-230.**

Prijanto **(1986).** **Soil** Hg mapping **at** Sikidang Field, Central Java, Indonesia. In: ***Proceedings of the 8th New Zealand Geothermal Workshop, 1986,*** **pp. 233-238.**

Sheppard, D., Faivre-Pierret, R.X., Orange, C.J. and Le Guern, F. (1990). **Soil** gas surveys: A cheaper alternative to geophysical survey: Three examples from the Taupo Volcanic Zone. In: ***Proceedings of the 12th New Zealand Geothermal Workshop, 1990,*** **pp. 125-128.**

Whitehead, **N.E. (1984).** Geothermal **prospecting** by **ground** radon measurements. ***Jnl. Volcanol. Geothem. Res.,*** Vol. **20(3/4), 213-229.**