CO_2-FLUX OF STEAMING GROUND AT KARAPITI, WAIRAKEI

CINDY A. WERNER[1], MANFRED P. HOCHSTEIN[2], & CHRIS J. BROMLEY[1]
1. Institute of Geological & Nuclear Sciences Limited, Wairakei, Taupo; c.bromley@gns.cri.nz
[2]Geology Dept. and Geothermal Institute, University of Auckland, Box 92019,Auckland

SUMMARY- The diffuse discharge of CO_2 over the 0.35 km^2 Karapiti steaming ground area was obtained from accumulation chamber measurements at sites where the soil steam flux had been measured or could be inferred from a separate heat flux survey. The distribution of CO_2 fluxes is skewed and measurements exhibit significant temporal and spatial variability. Allowing for a biogenic background flux, the geothermal emission for the whole area was found by integration of contours to be c. 6 t CO_2/d. Using the measured CO_2 and steam flux data, an apparent soil-gas ratio was computed which points to a similar emission rate (c. 7 t CO_2/d). The CO_2 discharged by all fumaroles was found to be 16 ± 2.3 t/d, suggesting that the total CO_2 discharge at Karapiti is c. 23 ± 7 t /d, and that most of the CO_2 is emitted through focussed venting. The CO_2 emission at Karapiti is moderate in comparison to that of other hydrothermal sites. It amounts only to c. 12 % of the total amount of CO_2 produced in recent years by exploitation of the nearby Wairakei geothermal reservoir.

1.0 INTRODUCTION

Assessment of natural- and exploitation-induced greenhouse emissions has become an important research topic concerning future energy development scenarios. With respect to geothermal energy, only a few studies are available which describe direct measurements of natural CO_2 emissions from geothermal and volcanic geothermal systems (e.g., Werner and Brantley, 2000; Bergfeld et al., 2001; Chiodini et al., 2001). Although CO_2 is transferred to the surface of high temperature systems together with water vapour, near-surface steam flux measurements have not been used for assessment of CO_2 emissions.

Since we had completed a detailed heat flux and steam flux study of the Karapiti steaming ground area (Hochstein and Bromley, in press; Bromley and Hochstein, in press), we could occupy prepared heat flux sites to measure directly the CO_2 flux using an accumulation chamber. The aim of the study was to assess the total CO_2 emission rate of the Karapiti area associated with concentrated (fumaroles) and diffuse steam discharge.

2.0 PREVIOUS LOCAL STUDIES

Geothermal gas emissions from the Karapiti steaming ground area have been monitored since 1960 to assess the response of large manifestations to the development of the Wairakei reservoir. CO_2/H_2O molar ratios of steam samples from selected fumaroles and steam vents were recorded and showed an almost twofold increase in average CO_2 concentration from 1961 to 1990 when an average molar (M) ratio of 190 ± 26 (mM CO_2/100M H_2O) was measured (Glover et al., 1999, 2001). Using appropriate heat loss estimates and assuming that all heat discharged is derived from ascending vapour, an approximate total CO_2 emission rate (c.30 t/d in 1988) was predicted.

Short-term daily variations in background CO_2 flux in the area (changes by a factor of c. 2) have been cited by Sheppard and Mroczek (2002). One of their monitoring sites was at the margin of the Karapiti area. These variations are most likely the result of diurnal variability of atmospheric pressure and temperatures changing near-surface soil conditions (e.g., Granieri et al., 2003).

Heat flux measurements across the Karapiti area during the last few years have shown that practically all visible steam is discharged by fumaroles and steam vents (c. 41 kg/s, transferring c. 107 MW); a smaller proportion is discharged by diffuse emission (c. 27.5 kg transferring c. 69 MW) across the 0.35 km^2 steaming ground area (Bromley and Hochstein, in press). Steam discharge by fumaroles and steam vents was assessed using direct measurements (Hochstein and Bromley, 2001). The diffuse steam flux through the soil was obtained from ground calorimeter studies; the mass flux and heat flux rate correlate well with the depths where boiling temperature prevails (Hochstein and Bromley, in press). The heat flux of the whole Karapiti area was assessed at 105 stations. The established network (Fig. 1) was the starting point for the soil CO_2 flux survey described below.

3.0 CO_2 FLUX MEASUREMENTS

CO_2 fluxes were measured using a West Systems accumulation chamber with a LI-COR LI-820 CO_2 infrared analyzer (0-2000 ppm). Accumulation chamber methods have been previously described (Werner and Brantly, 2000, Bergfeld et al., 2001).

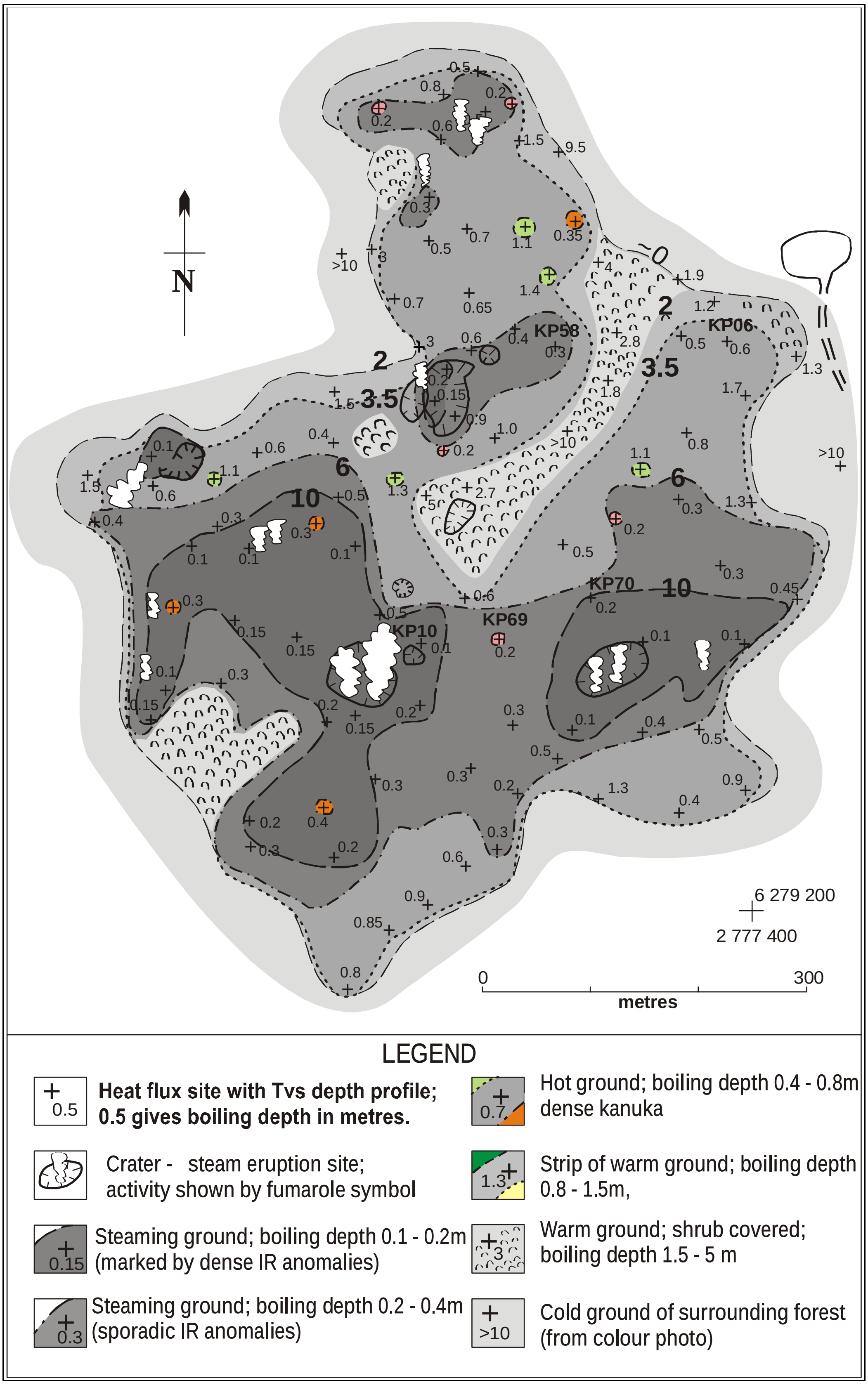

Fig.1: Map of Karapiti thermal area showing heat flux sites occupied in summer 2003/4 (figures show depth (rounded) to boiling temperature in m).The contour values give the shallow steam flux rate in kg m^{-2} d^{-1}.

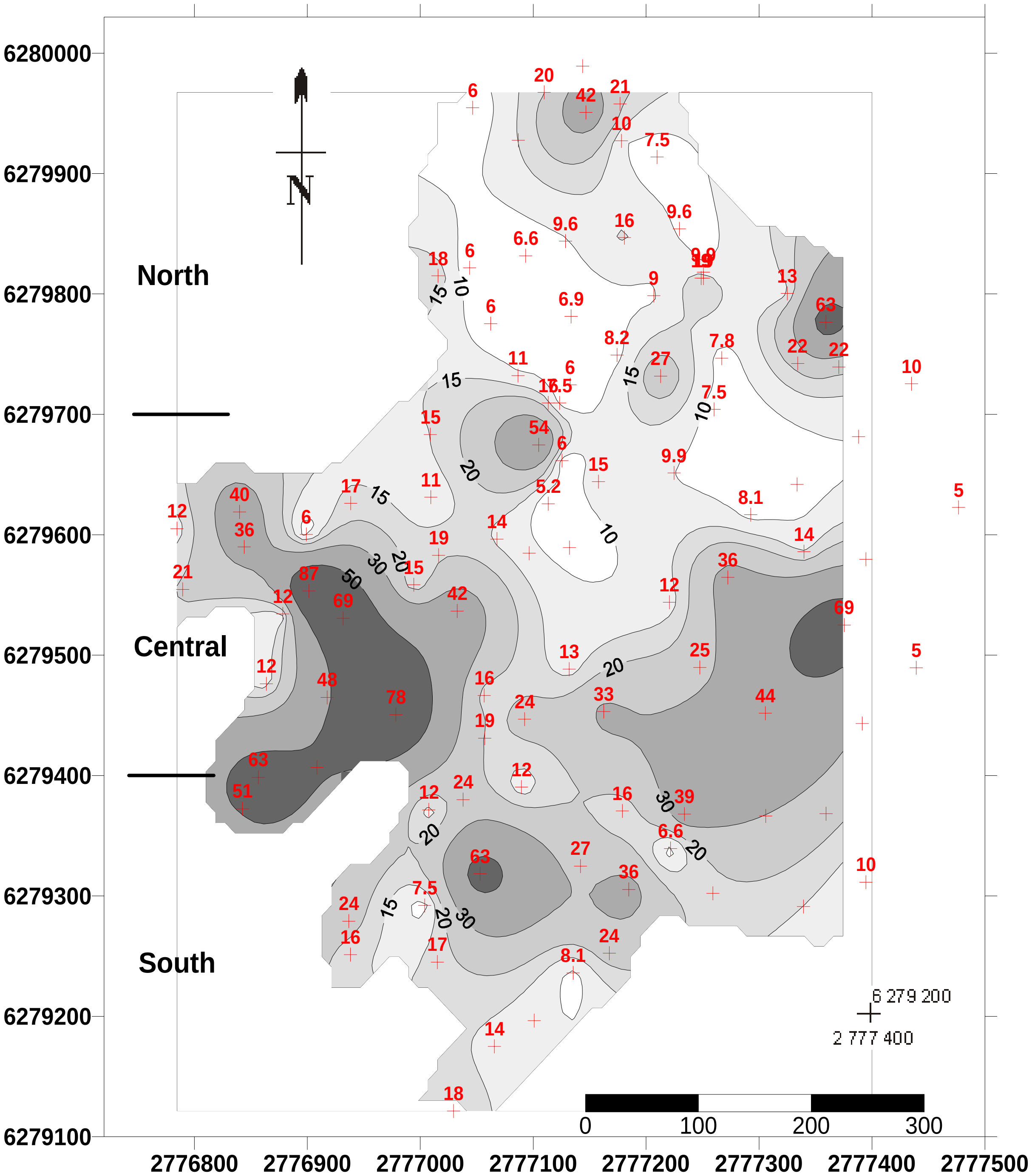

Fig 2: Map of CO_2 flux, same scale as that in Figure 1; CO_2 values are in (g m^{-2} d^{-1}). Contours along the eastern boundary are constrained by estimated values as shown (5, 10 g m^{-2} d^{-1}).

Reconnaissance measurements at Karapiti were made on 08.10.02 and 02.12.02 at 12 randomly selected sites of the heat flux network (Fig.1). The aim was to obtain an order of magnitude estimate for the diffuse steam emission at Karapiti, which had not been isolated from our (total) heat flux data at that time. Using the CO_2/H_2O gas ratios (Glover et al., 1999) and our CO_2 measurements, we estimated an average steam emission rate of the order of 20 kg (steam)/s for the diffusive component (Hochstein and Bromley, in press).

3.1 Detailed CO_2 flux survey

A more detailed survey was made on 23. and 24.03.04 after a method had been established to predict the diffusive steam flux using the depth of boiling temperature at each site. During the detailed CO_2 survey c. 75% of all sites shown in Fig.1 were occupied (roughly 25 to 50-m spacing); access problems prevented us from visiting the other sites. CO_2 fluxes were also measured at 7 additional sites. All sites occupied during that survey are shown in Fig.2.

For the heat flux survey the sites had been prepared in the form of small, level, almost circular platforms (diameter c. 0.3 m) from which plants had been removed. It was therefore assumed that the effect of biogenic CO_2 would be small. The measurements were repeated at 25 sites showing significant temporal and (close distance) spatial variations in CO_2 flux with repeat values being within ± 50% of the mean at thermal sites. Larger variations were observed over intense steaming ground where CO_2 gas had accumulated beneath a thin crust; readings from these sites were not used in the following analysis because they were not considered representative. Ground temperatures at 0.10 and 0.19 m depth were also taken at the same time the gas flux was measured.

Flux data were normalized to standard temperature and pressure but were not reduced for temporal drift. It was assumed that the resulting uncertainty produces random variations at all stations which would not affect significantly total emission estimates. A histogram of the data, all with low flux values between 5 and 90 (g m^{-2} d^{-1}), shows a log-normal distribution. A similar result had also been reported for CO_2 data from the Dixie Valley field (Bergfeld et al., 2001).

To map the data, a variogram was fitted and modelled using the untransformed data. The data were kriged, based on a sample spacing of ~ 8 m, and contoured. A contour map of the processed data (Fig. 2) shows that many sites with high heat flux, and those near intense steaming ground, also have elevated CO_2 fluxes, especially in the southern half of the survey area. Only a few measurements were made at stations lying outside the steaming ground area which was known from the ground temperatures and vegetation pattern (see Fig.1).

3.2 Total geothermal CO_2 emission rate

Two methods were used to calculate the emission rate from the area, both resulting in ~ 6 t CO_2/d. Volume calculations of the gridded (untransformed) data were performed based on an algorithm of the Surfer® programme assuming a 5 g m^{-2} d^{-1} background. This gave an estimate of c. 6.0 t CO_2/d. It can be compared with an estimate derived from integration of contours with log-normal intervals.. Allowing for a background value of 5 g m^{-2} d^{-1}, the lowest value at sites over cold ground, the emission rate for the diffuse degassing at Karapiti was c. 6.2 t CO_2/d. The uncertainty of this value is poorly defined, and is most likely affected by variability of fluxes at scales smaller than the sample spacing.

3.3 Assessment of the total diffuse CO_2 emission rate based on steam fluxes

The diffuse CO_2 emission rate at Karapiti can also be obtained from the known total diffuse steam discharged if a representative CO_2/H_2O ratio for the discharged fluids can be obtained. For this we computed the likely vapour flux (in g m^{-2} d^{-1}) beneath each site which is a function of the measured boiling depth (Hochstein and Bromley, in press). The uncertainty of the computed flux is for most stations within ± 20 % when compared with the flux measured at a small number of stations (17 out of 105). The near-surface vapour flux plotted against the ln (CO_2) flux for each site (Fig.3) shows a large scatter (R^2 = 0.35). The data, however, can be used to compute apparent CO_2/H_2O gas ratios for all sites; the computed values also show a log normal distribution. (Four anomalous values from cold ground sites at the margin were excluded). The mean, μ , and standard deviation, σ , of a log normal population is listed in standard texts (e.g. Till, 1971).

From the data in Fig.3 we found that: μ = 150 ± 110 (mM CO_2/100M H_2O) for n = 80. The rather high σ value reflects the wide scatter of the computed ratios; it is half an order of magnitude greater than the standard deviation of the same average ratio of fumarole gases analysed in 1990 when: μ = 190 ± 26 (mM CO_2/100M H_2O) for n = 24 (see Glover et al. 1999). The same ratio was obtained using our data of stations which lie in the southern part of the Karapiti area enclosed by the 10 kg m^{-2} d^{-1} steam flux contours (see Fig.1). For these stations the mean ratio is: μ = 190 ± 110 (mM CO_2/100M H_2O) for n = 14.

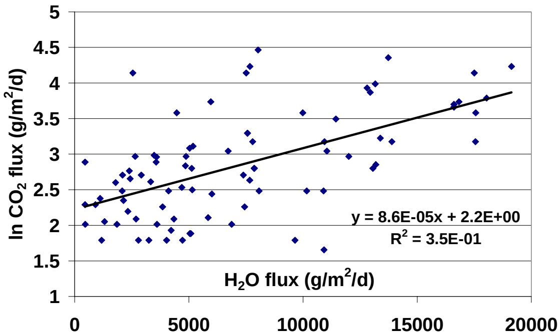

Figure 3: Plot of specific vapour mass flux versus ln (CO_2 flux) from all stations shown on Figure 2

The total CO_2 emission from the steaming ground can also be computed from the steam emission rate (26.5 ± 6 kg/s) and the computed mean gas ratio (150 ± 110 (mM CO_2/100M H_2O)) which gives a total emission rate of 8.4 t CO_2/d, or c. 6.7 t CO_2/d after subtracting a background value of 1.7 t/d.

This rate is close to that obtained from contouring of the measured soil fluxes lending confidence to the results.

The CO_2 emitted with steam discharged by the Karapiti fumaroles can also be assessed in the same way, yielding an emission rate of 16 ± 2.3 t CO_2/d. This value is only an estimate, since a steam emission rate of 41 ± 4 kg/s was measured in 2000, and the mean gas ratio quoted by Glover et al. (1999) dates back to 1990. A biogenic background emission was not subtracted from the estimate because of the inferred deeper origin of CO_2 and vapour discharged by the vents. The total amount of CO_2 discharged over the Karapiti area given by the combined concentrated discharge from fumaroles and the diffuse emission over the whole steaming ground area is therefore c. 23 ± 7 t CO_2/d.

4.0 LIKELY CAUSES OF THE CO_2 FLUX VARIATIONS

The large scatter of the data (Fig.3) and the different standard deviations of the mean gas ratios for 'deep' discharges from fumaroles and 'shallow' emissions from steaming ground indicate that in the latter case both enrichment and depletion of CO_2 occur at shallow levels on small-spatial scales. Our studies of heat transfer in steaming ground (Hochstein and Bromley, in press) has shown that a 'heat-pipe' mechanism operates at shallow soil levels (Fig.4) where vapour condenses at a shallow level above boiling point depth within a 'condensate layer'. Liquid droplets then descend into a deeper vapour-saturated layer where secondary evaporation occurs. In this setting, enrichment and depletion of CO_2 is most likely associated with the shallow 'condensate layer' which is typical for steaming ground sites. In a rising CO_2-vapour column, condensation of vapour could lead to a CO_2 (gas) enrichment above the condensate layer. On the other hand, condensation of water vapour could lead to saturated soil conditions thus decreasing soil permeability. This, in turn, could decrease CO_2 fluxing through the surface and, thus, reduce the apparent CO_2/H_2O flux ratio at the surface.

In steaming ground areas, the condensate layer is heated by the latent heat of condensation and is cooled at the top by shallow evaporation. Hence, there are two vapour components involved, namely a 'deeper' component, which ascends through the condensate layer to the surface, and a 'shallow' component which derives from evaporation at the top of the condensate layer (Fig.4). The processes of condensation and re-evaporation could also produce significant variations in the CO_2/H_2O gas ratio between nearby steaming ground sites.

It is also possible that the CO_2/H_2O gas ratio varies across the area due to changes in the hydrogeology. For example, boiling and degassing of groundwater as it flows laterally across the entire Karapiti area (from north to south) may lead to systematic changes in the CO_2/H_2O ratio. To check this, the mean and standard deviation of the CO_2/H_2O data in Fig.2 were computed for three adjacent sectors, assuming a log-normal distribution of data for each sector. The data from the southern and central sectors with steam flux values >10 kg m^{-2} d^{-1} (at 14 sites) near intense steaming ground were excluded. With respect to the common ratio unit of (mM CO_2/100M H_2O) the following values were obtained: for the northern sector μ_1 = 182 ± 145 (n = 26), the central sector: μ_2 = 131 ± 87 (n = 25), and for the southern sector: μ_3 = 93 ± 50 (n = 14). The hypothesis whether the mean in each sector comes from the same population was tested using the 'pooled variance' test (Till, 1971). This showed that the μ_1 and μ_3 populations differ at the p=0.95 confidence level. It can therefore be concluded that there is a system-scale overprint which causes a southward decrease in the CO_2/H_2O gas ratio in the Karapiti. area. A similar trend had been observed in 1961 for fumarole discharges although it had disappeared by 1990 (Glover et al., 1999). It appears now that the trend has been re-established.

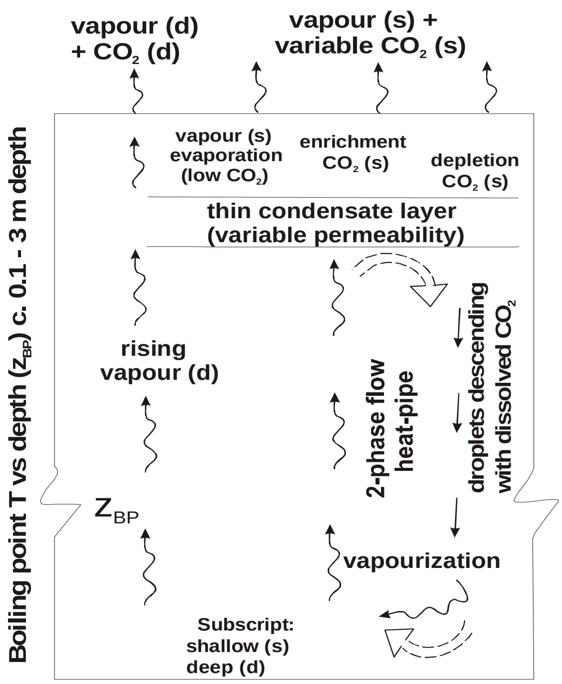

Fig.4: Schematic diagram showing inferred fluid and gas movements in steaming ground.

5.0 DISCUSSION

In comparison to similar surveys of other steaming ground areas, the CO_2 emission rate at Karapiti (c. 23 ± 7 t/d) is rather low. About 70% of the CO_2 is discharged by steam through fumaroles and visible steam vents. The remainder is from diffuse emission. The range of diffuse CO_2 fluxes is also low (5 to 90 g m^{-2} d^{-1}), but similar values occur elsewhere over steaming ground, for example, at the Dixie Valley (Nevada) geothermal field (Bergfeld et al., 2001). Higher CO_2 emissions were observed over steaming ground associated with the volcanic geothermal system at Campi Flegrei (Italy) where the total CO_2 emission over a c. 1 km^2 large area is c.1500 t/d (Chiodini et al., 2001). In between is the CO_2 discharge from the Mud Volcano area in Yellowstone National Park where c. 280 t/d emits over roughly the same area as that covered by the studies above (Werner and Brantley, 2000). The total CO_2 emission of all natural discharge features of the Wairakei system is greater, as shown by a reconnaissance study of Sheppard and Mroczek (2002). It is probably of the order of at least 50 t CO_2/ d. However, this inferred natural discharge is still half an order of magnitude less than the discharge of the Wairakei power plant where steamlines from the production field transported on average c. 200 t CO_2/ d in 2000 (Glover and Bacon, 2000).

In this study the combined use of steam and CO_2 fluxes at single sites in steaming ground allows an independent assessment of the CO_2 emission rates using site-specific CO_2 gas/steam ratios together with the steam mass flux rate of the whole steaming ground area. The correlation between single CO_2 and steam fluxes is poor, indicating that CO_2 fluxes and concentrations are modified by processes other than vapour transport. The large difference in the variance of CO_2/steam ratios from fumaroles and of diffuse discharges across small distances indicates that processes occur at shallow depths, presumably in connection with near-surface condensation and evaporation from the top of a shallow concealed 'condensate layer'. The processes which lead both to enhancement and depletion of CO_2/steam ratios have still to be studied in detail, but are most likely associated with a heat pipe mechanism and changes in near-surface permeability which control the vapour/gas transport at shallow depths in steaming ground.

6.0 ACKNOWLEDGEMENTS

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