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Carbon Dioxide Emissions from the Rotorua Hydrothermal System, New Zealand

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ABSTRACT

Carbon dioxide fluxes were measured at 952 locations across the greater Rotorua hydrothermal system in the Taupo Volcanic Zone of New Zealand during 2003. Measurements were concentrated in regions that previously exhibited elevated levels of carbon dioxide in soil gas measurements (20-50 m spacing), and also dispersed across the greater Rotorua city area (100-200 m spacing). Flux measurements and modeling concur with previous analysis of the hydrothermal system with upwelling regions showing the highest CO_2 emissions. The highest fluxes were measured in the Ngapuna region suggesting that flow into this area is the most primitive (i.e., least degassed). Similar high fluxes were measured in the Whakawareware, Arikikapakapa Golfcourse, and Kuirau park region suggesting partially degassed fluids supplying these regions. The greatest extents of degassing areas were observed in known thermal regions; however, elevated levels of soil CO_2 flux were also observed in isolated patches throughout residential and commercial areas presenting a probable health risk.

1. INTRODUCTION

The city of Rotorua is located in the central part of Taupo Volcanic Zone, which is an extensional depression that extends NE-SW on the northern island of New Zealand (Figure 1). Rotorua City lies at the southern end of the Rotorua Caldera, a nearly-circular infilled depression that is ~ 20x21 km, formed during the eruption of the Mamaku Ignimbrite (225ka, Milner, et al., 2003). Resistivity data shows that the Rotorua hydrothermal system (~25 km^2) underlies the entire area of the city and extends at least 2 km northward under Lake Rotorua (Bibby, et al., 1992). The thermal manifestation of this deep plume at the surface is isolated to three main areas shown in Figure 1. Within these regions the temperature at 1-m depth was at least five degrees C over ambient temperatures during the survey in 1971 (Thompson, 1971). Soil gas concentrations of CO_2 and H_2S were found to be elevated locally at sites within these thermal zones (Finlayson, 1992). Hydrothermal waters are primarily hosted in the Mamaku Ignimbrite (MI) and the post-caldera rhyolite domes, and the upflow of hot water and gases from the deeper hydrothermal system is thought to be partially controlled by the location of the post-caldera rhyolite domes. Current models based on drilling suggest that fluids rise in the east and southern regions of the city hear Ngapuna and Whakawareware in the fractured MI, and then flow eastward presumably in the MI until reaching the location of the buried rhyolite domes to the west (Wood, et al., 1992). At these locations fluids rise along the eastern side of the domes, surfacing near the Government Gardens and the Arikikapakapa Golfcourse. The domes are faulted roughly NE-SW providing preferred pathways for the release of deeply-derived hydrothermal fluids and gas. An additional upflow is located in the Kuirau Park region owing to the Kuirau Fault along the western edge of the northern rhyolite dome. Geochemical analysis of fluids support separate upflows in these three regions with the most primitive upflow in the eastern regions (Giggenbach, et al., 1992). Within the greater Rotorua City

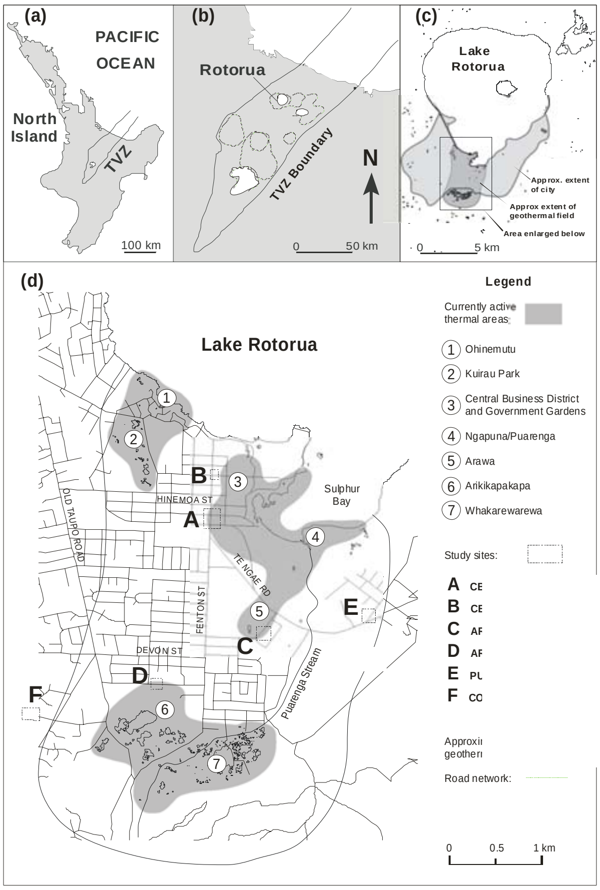

Figure 1. Location of the Rotorua geothermal system. (a) shows the position of the Taupo Volcanic Zone (TVZ) within the North Island of New Zealand, (b) shows the Rotorua caldera boundary in context of other volcanic calderas in New Zealand, (c) light grey is the extent of the city and the dark grey is the extent of the subaerial portion of the geothermal system, and (d) shows the street map of Rotorua City and the major regions of thermal manifestations with in the central Rotorua city limits (modified from Durrand and Scott, 2003, capital letters were their sample sites).

region degassed hydrothermal waters exist at relatively cooler temperatures within the northern and southern domes. These aquifers have been heavily exploited for domestic use (Wood, et al., 1992).

The current survey was performed as part of an effort to better define the health risk associated with the Rotorua hydrothermal system. The effort was undertaken to determine what levels of CO_2 flux exist across the greater Rotorua region, both within developed and undeveloped regions. Obviously the regions around the central business district have been extensively modified from a natural state in part to mitigate the problems associated with geothermal gas fluxes. However, continued problems occur across the city where soil gas infiltrates and collects in building areas posing a significant health hazard (Durand and Scott, 2003). The present study could be used as an indication of location, spatial extent, and magnitude of gas fluxes that occur across the city of Rotorua, and could be used in the future as a guide to high risk areas.

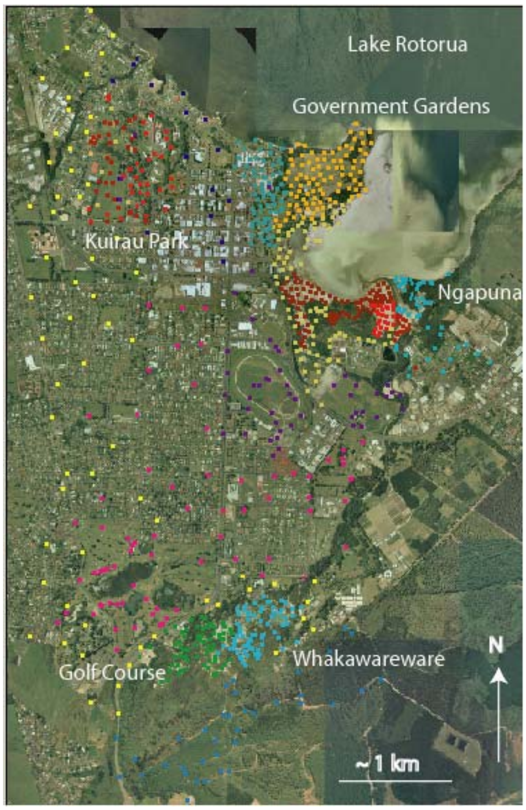

Figure 2: Airphoto of the Rotorua City. Each flux measurement location is shown with a dot. Each color represents one day of sampling.

2. METHODS

CO_2 fluxes were measured at 952 locations across Rotorua city (~ 16 km^2, Figure 1). Measurement spacing varied between ~ 25 and 50 m in known thermal areas (Kuirau Park, Government Gardens and Sulfur Bay, Ngapuna, Whakawareware, and the Arikikapakapa golf course) and up to 100-200 m in non-thermal areas. Measurement sites included locations where soil gas concentration measurements had been made in the past (Finneson et al., 1992). Measurements were completed mainly between December, 2002 and March, 2003, although Whakawareware was surveyed in June-August, 2003. All measurements were made following 3-days of dry weather using a West Systems accumulation chamber and a LICOR LI-820 infrared gas analyzer. Soil temperatures were measured at 10 cm depth at all sites where possible. Measurement techniques and calculations performed to the raw data have been described elsewhere (Werner, et al., 2000).

Fluxes were analyzed using the sequential Gaussian simulation algorithm (sGs) by the program sgsim (Deutsch and Journel, 1998). Details of sGs simulations of CO_2 flux data have been described elsewhere (Cardellini, et al., 2003). The analysis included normal-score transformation of the data, variogram modeling, and 100 realizations of the flux data over the grid were modeled with a cell size of 20-m.

3. RESULTS

CO_2 fluxes and soil temperatures ranged from not detectable to 11535 gm^{-2}d^{-1} and 5 to 100 ^{o}C, respectively.

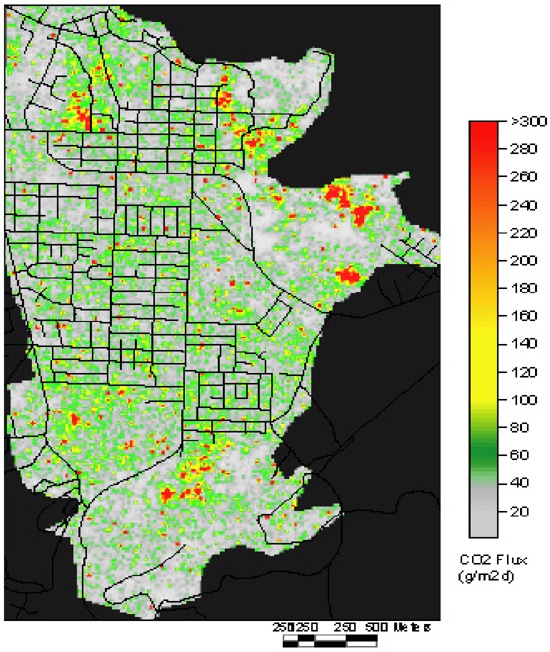

Figure 3: Map of CO_2 fluxes modeled for the Rotorua region.

The arithmetic and declustered means of the entire data set were 113 and 94 gm^{-2}d^{-1}, respectively, with a coefficient of variation of 5. The distribution of fluxes was skewed, but not strictly lognormal based on the D'Agostino's goodness of fit test. CO_2 fluxes were spatially variable across the study area but generally highest in previously defined thermal areas (Table 1, and Figure 2). Fluxes measured in the Ngapuna area were higher than in other thermal areas. For example, 12 measurements exceeded 1000 gm^{-2}d^{-1} at Ngapuna, whereas all of the other regions had $\leq$ 2 measurements over this value. Regions of high flux

Table 1. CO_2 fluxes in thermal areas of Rotorua

	CO_2 (gm^{-2}d^{-1})		Temp (^{o}C)	
	max.	min	max	min
1(270)*	11535	nd#	100	6.1
2(160)*	350	nd	54	17.5
3(74)*	2094	nd	99	15.8
4(133)*	2835	nd	100	5
5(39)*	2618	nd	77	15.1

* 1=Ngapuna, 2=Government Gardens, 3=Kuirau Park, 4=Whakawareware, 5=Golfcourse; the number in parenthesis is the number of measurement sites
# = not detected

extended over hundreds of meters in previously defined thermal areas (e.g., Ngapuna, Whakawareware, Figure 3), and were typically spatially consistent with regions of altered ground and thermal springs. Isolated highs fluxes were measured across the rest of the Rotorua region sometimes occurring in residential areas, but were typically not modeled to extend over more than 25-50 meters.

A weak correlation existed between the log of CO_2 fluxes and the log of soil temperatures (Figure 4). Generally fluxes >100 $gm^{-2}d^{-1}$ had soil temperatures that exceeded 20^oC at 10 cm depth. Interestingly, the two highest fluxes were measured in an area with relatively cool soil temperatures.

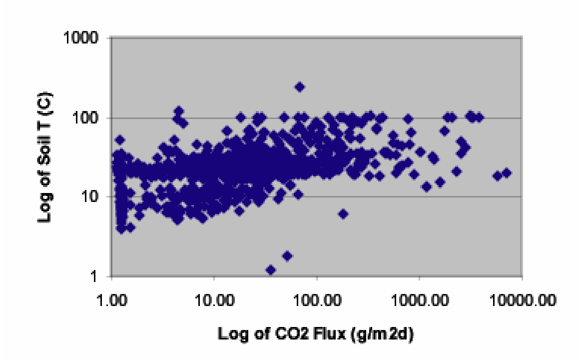

Figure 4: Log of soil temperatures plotted against log of CO_2 fluxes.

4. DISCUSSION

The levels of CO_2 flux measured in the Rotorua region are as high as those measured on active volcanoes (e.g., maximum measured fluxes at White Island were ~ 8000 $gm^{-2}d^{-1}$) and are up to 3 orders of magnitude higher than typical biogenic fluxes (e.g., Raich and Schlesinger, 1992). The measurements of CO_2 flux across the Rotorua geothermal system are consistent with previous models of upflow of geothermal fluids in previously mapped thermal regions. The Ngapuna region displayed the highest fluxes, and the greatest number of high fluxes of any area in the study, suggesting that this area is likely indeed the main upflow for the geothermal system releasing the greatest proportion of CO_2 from the geothermal fluids with depressurization and boiling (e.g., Finlayson, 1992). This finding is also consistent with the high Cl^- being observed in a spring in the Ngapuna region. Equally high fluxes were observed at Whakawareware, the Arikikapakapa Golfcourse, and Kuirau park (all $\leq$ 3000 $gm^{-2}d^{-1}$), suggesting the fluids that supply this region are likely partially degassed in comparison to those emitting at Ngapuna. A concentrated zone of moderately high (max = 350 $gm^{-2}d^{-1}$), yet spatially extensive, flux was observed in the Government Gardens region along the zone where the edge of the rhyollite domes are mapped. Our data supports the existence of a secondary upflow at this boundary, and that these fluids are likely highly degassed over those supplying the Ngapuna region. The high soil gas fluxes observed in the northern portion of the Arikikapakapa golfcourse are thought to result of upflow along the southern boundary of the southern dome (e.g., Finlayson, 1992), but there is no evidence that these fluids are any more degassed than those supplying Whakawareware. The highest fluxes in this area tend to have a NE-SW trend consistent with regional faulting. It could be argued that the upflow in the Whakawareware area likewise has a roughly NE-SW trend, or perhaps a more northerly trend that follows the trace of the Rotoatamaheke fault as mapped by Wood (1992). Finally, high CO_2 fluxes were observed in Kuirau Park and are consistent with models of upflow along the Kuirau fault as mapped by Wood (1992).

Isolated patches of high CO_2 flux occur across the greater Rotorua region and are most likely a result in local permeability increases in near-surface conditions. Geothermal waters have been mapped across the greater Rotorua area at depth, providing geothermal water to many properties in the Rotorua region. While there is the added benefit of geothermal water, there is also a risk of increased gas fluxes on certain properties as shown by detailed mapping. The isolated patches mapped here do not seem to have any particular spatial arrangement, but are consistent with the existence of high gas concentrations in wells in the central regions (Glover and Heinz, 1985). Such localized patches of high flux are small in spatial extent (typically < 50 m), but of high enough flux that likely properties should not be built upon these regions. Typically temperature surveys are used as a means to determine if a potential property is located in a geothermally affected region. However, as high CO_2 flux is not always consistent with high soil temperatures, this implies that perhaps additional surveys should be completed prior to building consent in the future. This suggestion is consistent with the recent investigation of residential and commercial properties across the greater Rotorua region where levels of CO_2 and H_2S found to be at lethal levels in enclosed spaces (Durrand and Scott, 2003).

5. CONCLUSIONS

The CO_2 flux survey at Rotorua has generally confirmed the conclusions of other studies regarding the general flow patterns of the Rotorua geothermal system. The fluxes measured are consistent with the level of fluxes measured in other volcanic and geothermal regions worldwide. The highest fluxes were observed in the region previously postulated as main upflow regions of the geothermal system, and additional high-flux areas were observed in faulted regions and at the boarders of previously mapped subsurface changes in lithology. While the greatest extents of degassing areas were observed in known thermal regions previously set aside as reserves or parks, elevated levels of soil CO_2 flux were also observed in residential and commercial areas and present a probable isolated health hazard. If building were to proceed in previously undeveloped regions the future, we suggest that additional surveys of CO_2 fluxes over property would provide a fast and effective way of detecting geothermal upflow in spatially small areas. This is especially important in regions where there is not thermal indication of hydrothermal activity at depth.

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