SOIL GAS ANALYSES AS INDICATOR OF FAULT ZONES – EXAMPLES FROM THE TAUPO VOLCANIC ZONE

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ABSTRACT

Different analytical approaches to measuring diffuse soil gas emissions were tested for their capability to indicate permeable fault segments in areas with and without obvious geothermal manifestations on the surface environment. The methods were applied in three active normal faulting regions in the Taupo Volcanic Zone (Reporoa, Ngapouri, Maleme). Gases such as carbon dioxide and radon are proven tracers for geothermal subsurface activity. Hence, an increase in emissions across and close to faults could be indicative for permeable fracture zones bearing geothermal fluids.

Carbon dioxide efflux and concentration measurements were performed using the accumulation chamber method and an open-path Tunable Diode Laser (TDL), respectively. Furthermore, radon and thoron activity measurements in soil gas have been performed by alpha spectroscopy. Gamma spectroscopy was used as a complementary method to detect solid nuclides (e.g., ^{214}Bi, ^{208}Tl) originating from radiogenic minerals in the subsurface. Additionally, an extended soil gas survey was performed in one of the study areas by taking soil gas samples and performing chemical analyses (e.g., He, Ar, Ne, H_2, N_2, O_2, CH_4) by Quadrupole Mass Spectrometry (QMS) and micro-Gas-Chromatography (µGC), as well as carbon isotopic analysis of the soil gas CO_2 (δ^{13}C-CO_2) by an Isotopic Ratio Mass Spectrometer (IRMS).

A further objective of this study was the comparison of different methods on structural-geological questions and their correlation to each other. Preliminary results suggest that the combination of different techniques provides a comprehensive understanding of the fluid migration along fault zones and in geothermal systems; however, the correlation between different parameters requires additional investigation.

1. INTRODUCTION

1.1 Fault zone analysis

The development of geothermal reservoirs requires detailed understanding of the subsurface in particular structural characteristics. Hence the analysis of fault zones is not only of scientific, but also of economic interest. Detailed geological mapping, geophysical methods, etc. provide information about structural properties of a fault (e.g. vertical offset or displacement rate). The use of different in-situ techniques for the assessment of diffuse degassing processes provides an overall picture about spatial and temporal changes in fault permeability inside a study area. Herein, different questions have been addressed to the different sites.

1.2 Diffuse degassing processes

Diffuse degassing processes are used to monitor active volcanic areas where continuous measurement of gas fluxes (e.g. CO_2, H_2S, ^{222}Rn) provides input to volcanic hazard analysis. Nevertheless, you can find high gas fluxes away from active volcanic centers where deep reaching faults act as preferential pathways for CO_2 or trace gases (^{222}Rn, He) and connect the geothermal reservoir with the surface. Areas of tectonic degassing, e.g. Apennines (Chiodini et al., 2004), Basin and Range Province (Jolie et al., 2015) are likely to be underestimated in the global CO_2 budget, although there is high gas fluxes which originate from deep magma bodies (Lee et al., 2016). From the perspective of geothermal resource evaluation, the mapping of relevant geothermal gases across active fault lines is important to understand the properties of a fault (e.g., permeability), and hence their potential as a well target, as well as understanding the structural-geological characteristics.

1.3 Geological setting and study areas

The Taupo Volcanic Zone (TVZ) is located on the North Island of New Zealand and is recognized one of the most productive areas of Quaternary silicic volcanism in the world. Intense volcanism as well as geothermal surface manifestations follow the rifting arc structure resulting from the extension of the Australian plate (Wilson and Rowland, 2015). Due to the oblique subduction of the Pacific plate towards the west beneath the Australian plate (Rowland and Simmons, 2012; Lamb and Smith, 2013), the annual extension rate across the TVZ is up to 15 mm; consequently a dense system of active normal faults developed (Fig. 1) (Rowland et al., 2010; Villamor and Berryman, 2001). The Taupo Fault Belt (TFB) named by Grindley (1960) also referred as Taupo Rift is the visible expression of rift related faulting and extends from the Bay of Plenty coast in the northeast to Mt Ruapehu, an andesitic stratovolcano (Kilgour et al., 2013) in the southwest. Predominantly active normal faults are distributed in an area 40 km wide with opposing northwest- and southeast- facing fault dips defining the rift axis and the largest fault displacement rates

(1-2 km) along the eastern rift margin (Rowland and Sibson, 2001; Seebeck et al., 2014). Through seismic tomography deep intraslap earthquakes could be recorded up to a depth of 600 km just below the Taupo Rift with the NE – SW striking slap following the general trend of the TFB (Boddington et al., 2004; Reyners et al., 2006). The beginning of the convergence of the Pacific plate beneath the Australian plate dates from ~16Myr ago (Wilson & Rowland, 2015).

Although the majority of faults in the TFB is traced by aerial photographs, digital elevation models as well as detailed geological surface mapping, it is often difficult to distinguish between individual faults. Faulting varies spatially and temporally. Towards the rift shoulders the faults tend to be longer and continuous (e.g. 20-30km) and cut through volcanic surfaces or basement whereas a dense network of short segmented faults (e.g. 1-4km length) is observed towards the rift axis cutting through young volcanic and fluvial surfaces (Seebeck et al., 2014; Villamor & Berryman, 2001; Grindley 1960). Faults have the capability to be hydraulic as well as gas conductors connecting shallow and deep geological environments. This is mainly depending on the permeability of a fault which is influenced by structural properties (e.g., slip rate), the temporal evolution of a fault zone, the surrounding lithology and state of stress (Smith et al., 1991). In geothermal systems faults are preferential targets for exploration and production of the reservoir, since they often act as major conduits (i.e., upflow zones) for hot fluids and gases (Bense et al., 2013; Caine et al., 1996).

1.3.1 Reporoa

The Reporoa geothermal system is a NE-SW elongated basin located to the South of Waiotapu, the largest geothermal field in the Taupo Volcanic Zone. The Paeroa Range in the northwest and the Kaingaroa Plateau in the southeast are limiting the basin. Nairn et al. (1994) described the Reporoa depression as a caldera and the source for the Kaingaroa Ignimbrites which got deposited as a rhyolitic pyroclastic flow 0.24 Ma ago. Although there is no obvious fault scarps at the surface it is known that inferred normal faults are dominating in the area and are possible pathways for hydrothermal fluids (Bignall, 1990). It was previously argued the Reporoa system is hydraulically linked to the Waiotapu system (Healy and Hochstein, 1973), and that Reporoa comprises an individual geothermal system (Hedenquist and Browne, 1989). Analyses of surface degassing and emanation processes have been applied to evaluate if further indications of a proposed linkage can be found.

1.3.2 Ngapouri

As a major branch of the Paeroa Fault the strike of the Ngapouri Fault with 55° follows the trend of the majority of faults (40°-60°) within the TFB (Rowland & Sibson, 2001; Villamor & Berryman, 2001; Nairn, 1973). With a length of about 15 km the downthrown block is dipping to northwest due to normal faulting. The fault passes from the Paeroa Trig, along the hummocky tongue shaped slopes of Paeroa Range (Newson et al., 2002), touches Ngapouri Lake on the eastern shore and continues until Lake Okaru in the north (Grindley, 1963). It crosses two dacite volcanoes Maungakakaramea (Rainbow mountain) to the northeast and Maungaongaonga to the northwest (Hedenquist and Henley, 1985). Although the fault scarps are poorly preserved, due to vegetation or partial burial by recent ash, the fault has several young hydrothermal explosion craters as there is also steaming ground scattered along the fault zone which helps to plot the trace (Healy, 1974; Hedenquist & Henley, 1985; Villamor & Berryman, 2001). A previous study on excavated trenches along Ngapouri Fault provides results for vertical offsets and mean vertical displacement rates (0.23 ± 0.001 mm/yr) of > 0.23 Ma ignimbrites (Villamor & Berryman, 2001; Berryman et al., in prep). Both CO_2 flux, CO_2 and Rn concentration measurements were applied at the Southern segment of Ngapouri Fault Zone. In this part, two distinct fault lineaments were mapped (Villamor and Berryman, 2001). Further to the south both faults merge and get interrupted by a rhyolite ignimbrite hill (Leonard et al., 2010). Ngapouri fault forms the eastern shoulder of the TFB and limits the Waiotapu-Waikiti geothermal system. Two areas of steaming ground are situated at the southern end of the fault and some fumaroles at the southeastern corner of Maungaongaonga which lead to the presumption of a connection in depth between the Waiotapu-Waikiti geothermal system southward along Ngapouri fault to small areas of geothermal surface activity.

1.3.3 Maleme

The Maleme Fault Zone (MFZ) is a complex network of up to 16 fault strands which form a 2.5 km wide graben inside the Ngakuru subdomain in which the northern part defines the central axis of the TFB and is focus of this study. The steeply (~75°) dipping faults splay and merge at different positions and change their general trend from 55° in the south to 35° in the north over a 19 km long section. A sequence of lacustrine and young volcanic deposits is displaced by about 3.55 ± 0.3 mm/a over the past 20000 years. Especially in the northern part of the MFZ scarp heights can be between 1-15 m high (Villamor & Berryman, 2001; Tronicke et al., 2006). Five traverses across several fault strands were chosen to measure Radon/Thoron concentration and CO_2 flux. The aim was to cover as many fault strands as possible to see a change in gas anomalies from the tectonically most active part-the graben axis towards the west-out of the graben. Additionally, it was of interest to understand whether some of the fault strands are linked to each other in the subsurface where no surface expression is visible.

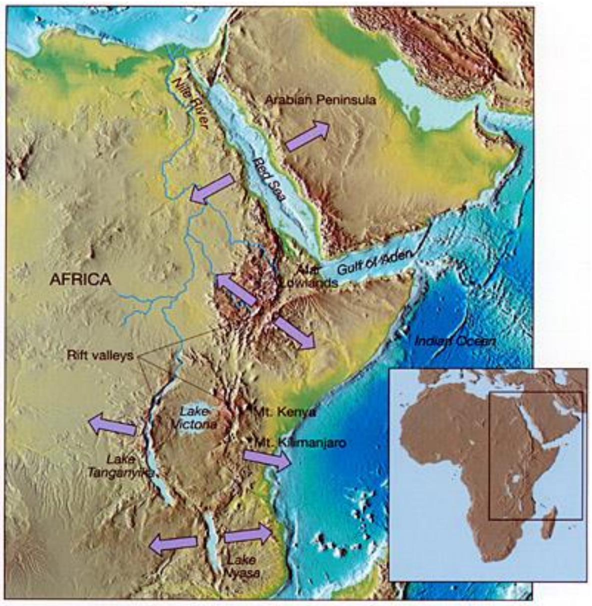

Figure 1: Taupo Volcanic Zone with location of selected study areas.

2. METHODS

A variety of seven different methods have been applied at the selected study areas during field surveys in June/July 2014 and between October 2015 and February 2016. Measurements have been arranged as regular grids (point spacing ranging from 25-100 m) or single profiles perpendicular to major fault orientation.

2.1 Accumulation chamber

Measurements of diffuse CO_2 emission rates were performed according to the accumulation chamber method. For this study a portable flux meter with a LICOR LI-820 single path, dual wavelength, nondispersive infrared carbon dioxide analyzer was used (West Systems Ltd., 2002). CO_2 efflux measurements are widespread in different geoscientific disciplines, such as volcano and environmental monitoring. Herein, we intend to use increased gas emissions as an indicator of structural permeability along fault zones (Jolie et al., 2015), e.g., between Reporoa and Waiotapu.

2.2 Tunable diode laser (TDL)

The tunable diode laser spectroscopy (TDLS) technique consists of the measurement of gas mixing ratio based on the absorption of Infra-Red radiation by the target gas. The TDL used in this study consists of a GasFinder 2.0 Tunable Diode Laser (Boreal Laser Inc), an Infra-Red transmitter/receiver (transceiver) unit that can be used to measure CO_2 mixing ratios over linear paths of up to 1 km distance. A laser light emitted from the transceiver propagates through the atmosphere to a retro-reflector array and returns to the transceiver where it is focused onto a photodiode detector. These two signals are converted into electrical waveforms. A micro controller is processing these waveforms to determine the actual concentration of CO_2. You can see the computed gas concentration on the back panel of the monitor which is connected with a computer who can display and store the data (Myers et al., 2000). It is a portable tool which shows CO_2 concentration in ppm (parts per million) and has been used for monitoring CO_2 degassing in volcanic areas where we usually find high concentration of CO_2 (Mazot et al, 2012).

2.3 Alpha spectroscopy

Radon ^{222}Rn and thoron ^{220}Rn activity concentration in soil gas samples have been determined by a radiometric in-situ measurement of their short living radon daughter products. Increased radon ^{222}Rn activity concentration can be correlated with deep fracture zones.

2.4 Gamma spectroscopy

The gamma radiation of three characteristic solid nuclides (^{214}Bi, ^{208}Tl, ^{40}K) was determined to deduce the local dose rates. ^{214}Bi and ^{208}Tl are indicative of deep-reaching fracture zones.

2.5 Quadrupole Mass Spectrometry (QMS)

Short description of the method and what it can be used for.

2.6 Micro-Gas-Chromatography (μGC)

Short description of the method and what it can be used for

2.7 Isotopic Ratio Mass Spectrometer (IRMS)

Carbon isotopic analysis of the soil gas CO_2 ($\delta^{13}C$-CO_2). Short description of the method and what it can be used for.

3. PRELIMINARY RESULTS

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4. DISCUSSION AND CONCLUSION

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