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Analysing hidden messages in high temperature fumarolic emissions (16/726)

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Key words

Volcanic fumarole, high temperature gas emission, magma-hydrothermal interface, autonomous gas measurement

Summary

Fumarolic emissions from active volcanoes are typically comprised of gases that are not long removed from their parental magmas. As such, they carry a wealth of information about the nature of those melt(s), but also about the journey the vapours have had en route to the surface. Although we have been studying volcanic volatile emission chemistries in campaign fashion for over 40 years in New Zealand, we actually have little idea of what influences their behaviour over short time scales, the intricacies of the interactions between magmatic volatile streams and their enclosing hydrothermal system(s), or the ways in which the gas streams respond to periods of volcanic unrest.

In this study, we take a 3-pronged approach to characterising fumarole behaviour. First, we develop a real time, autonomous data station for deployment onto the highest temperature fumarole on the main crater floor of White Island (so-called Fumarole 0) which will record and telemeter key physical and chemical parameters back to the mainland in near-real time. Secondly, we conduct a first ever resistive tomographic survey of the subsurface conduit to ascertain the nature of the interaction between the fumarolic gases and the enclosing hydrothermal fluids; and 3) we develop a numerical model of fumarolic environments with which we can test the impacts of varying key parameters.

Introduction

Gas emissions from active volcanoes carry a wealth of information regarding the state of unrest of the host volcano. The gases carry thermodynamic equilibrium information which inform on subsurface intensive variables (e.g., Giggenbach, 1987), but there are also inherent chemical and isotopic signatures which provide insights into the source contributions (i.e., magmatic, hydrothermal or meteoric) to the discharges (e.g., Allard et al., 1991; Fischer et al., 1998; Hilton, et al., 2002).

Principally through the early work of Werner Giggenbach, New Zealand has one of the most complete records of campaign-style fumarolic data from its active volcanoes in the world, with the most intensive data stream coming from White Island. Even so, the frequency of data collection has been low – half yearly sampling over Giggenbach's tenure (1970's – early 1990's), and quarterly since then. The truth is, we have little idea of how the fumaroles behave in the short- to medium-term (hours, days, weeks), and we more than likely have a very incomplete understanding regarding processes operating in the sub-surface. Indeed, a recent study at Volcano (Montegrossi et al., 2008) revealed that over the course of some 24 hours, a single fumarole displayed hitherto unrecognised cyclic compositional variability with respect to S gases. Interestingly, minor compositional variability has also been observed over the span of even ~ 90 minutes from Fumarole 0 at White Island, whereas large variability in discharge characteristics (predominantly pressure cycling) has been observed first-hand on the Dome Fumarole in the eruption crater complex. Such variations provide clues as to physical reservoir processes within the magmatic-hydrothermal environment, processes which may be critical to our understanding of the plumbing and inherent hazards presented by these systems.

Real time monitoring of fumarolic emissions has long been a goal of researchers studying volcanic gas emissions, but the technological challenges have been difficult to surmount. First, there is the issue of data transfer which until recently has been the domain of the GeoNet network on White Island. GeoNet, however, made the decision in 2017 that they would not accommodate any data transmission from this station through its radio network on the island to the mainland, for reasons that remain unknown to this day. Fortunately, we have been able to circumvent this problem through the incorporation of satellite technology with this new station.

An even more serious challenge, however, is that of keeping such instrumentation running autonomously in the remote, extremely harsh, corrosive environment on the crater floor of White Island (Fig. 1). As outlined below, we have developed a deployment protocol that minimises exposure, and thereby degradation, of the various electronic components at the site. Furthermore, we have chosen analytical instruments that require an absolute minimum of intervention, which is of course key to any autonomous system.

Fig. 1. F0 site on White Island. Elemental sulfur forms the chimney around the vents, and the area where the installation will reside is periodically bathed in emissions, hence the requirement for effective protection from the corrosive gases.

Understanding how magmatic fumarolic gases interact with the hydrothermal systems through which they flow is difficult to ascertain, if only because this is all taking place below the surface. Giggenbach (1987) and Giggenbach and Sheppard (1989) deduced from observed chemical variability with time that the phase state behaviour of the near-conduit environment is in delicate balance with the pressure and temperature of the source gases. In effect, they proposed vapour, 2-phase vapour-liquid and single-phase liquid envelopes surrounding fumarolic conduits expand and contract with varying heat and mass inputs from the source. The scale over which this occurs is completely unknown, as are the fluid dynamics in the immediate vicinity of the conduits, a problem which lends itself to numerical simulation.

The work undertaken here is co-funded with SSIF (Hazards Platform), and to a lesser extent, GeoNet operational support. As an integrated work package, the following discussion around the scope of the study makes no attempt to split out which funding streams are paying for what work component, as is integrated at all levels.

Objectives

The objectives of the “Fumarole 0 Project” are three-fold:

- Enhance our understanding of the physical and chemical processes operating in high-temperature fumaroles;
- Use this understanding to constrain and quantify forward numerical model(s) of fumarolic environments; and
- Develop criteria for assessing trending levels of volcanic unrest for White Island, in conjunction with all other observables from the volcano.

Within these broader objectives reside the following tasks:

- Determine the principal chemical and physical parameters/indicators to monitor that will best delineate processes active in the subsurface;
- Construct and deploy an autonomous chemical and physical monitoring platform on an active fumarole at White Island;
- Apply Resistive Tomography to image the resistivity structure of the F0 conduit in the subsurface, and provide a datum for future comparison;
- Develop forward numerical heat and mass transport simulations (TOUGH2) of fumarolic environments that will assist in both evaluating and monitoring the phase state of the fumarolic environment through time.

Conclusions and key findings

Selection of Key Chemical and Physical Parameters to Monitor

Selection of chemical monitoring parameters for the autonomous system at White Island has been guided largely by observed variations in chemical and isotopic signatures derived from campaign measurements of fumarole F0 discharges through time. The decision around the optimal number of analytes to monitor is based on two principle criteria, namely 1) which parameter(s) would be most illustrative of variability of magmatic vs hydrothermal gas inputs; and 2) which parameters would signal changing compositions of the magmatic component, perhaps pointing to increasing volcanic unrest.

Key ratios of the main gas species from campaign measurements of F0 emissions since 2009, and their respective emission temperatures, are plotted in Fig. 2 as functions of time.

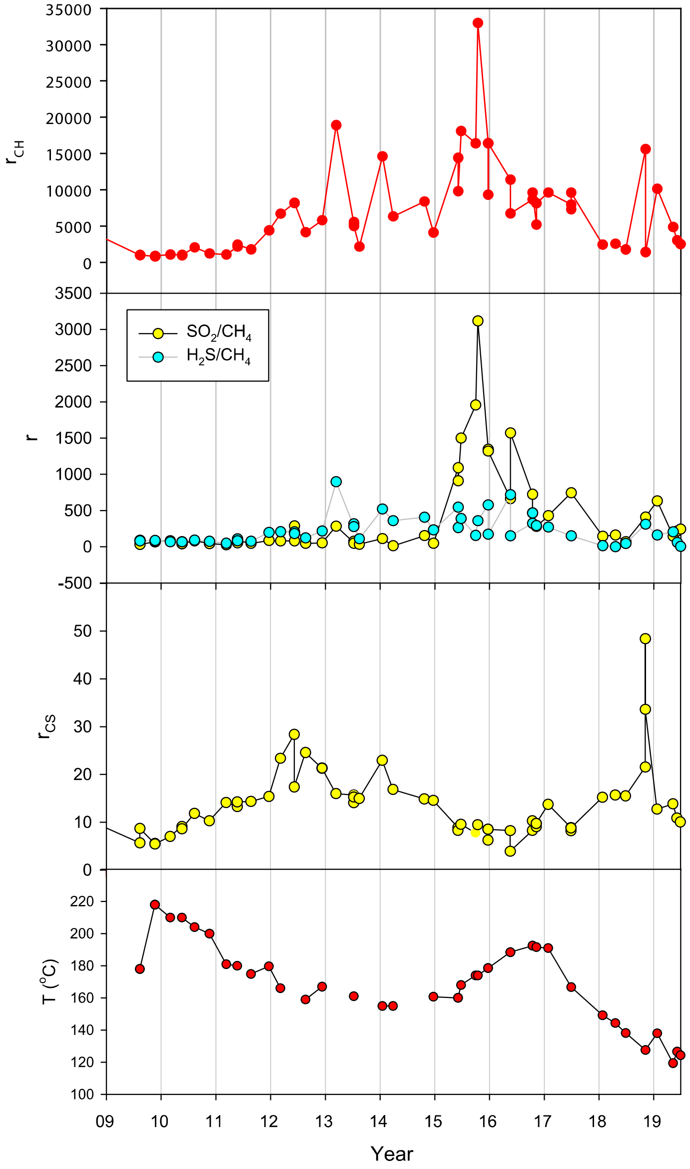


Fig. 2. Component ratios in F0 discharges with time. $r_{CH} = CO_2/CH_4$, and $r_{CS} = CO_2/S_{tot}$. Fumarole temperatures vary by ca. 100 °C over the 10 year period shown here, with maximum temperatures exceeding 220 °C measured in 2009.

Fumarole F0 developed from weakly steaming ground to an audible emission with a temperature of 125 °C over a matter of months in 2005. Pressures increased quite abruptly in 2009, however, and by the end of that year discharge temperatures had reached a maximum value of 218 °C. At that time, the volcano was quiescent, as demonstrated by the formation of crater lakes in the eruption crater complex (Christenson et al., 2017).

Given that we will necessarily sample the plume of the fumarole rather than piping fumarolic flow directly into the instruments (see discussion below around system design for this), the gas sample will necessarily consist of a mixture of fumarolic and atmospheric gases. Therefore, our focus is not on the absolute concentrations of selected species in the emission per se, but rather the component ratios amongst the relevant gas species CO_2, SO_2 and CH_4, as it is these ratios that carry the relevant information on source behaviour.

The hydrocarbon CH_4 is typically found in geothermal systems, where it is derived from the thermogenic decomposition of organic matter in sedimentary materials (i.e., kerogen; Taran et al., 2003). Importantly, CH_4 does not derive from magma (Chiodini, 2009; Giggenbach, 1987). CO_2, on the other hand, is typically found in both magmatic and hydrothermal environments, but is universally sourced from magma. Hence, the ratio of CO_2/CH_4 is a powerful indicator of relative component fractions of magmatic and hydrothermal endmembers, and therefore can be used as a sensitive indicator of changing levels of magmatic unrest in magmatic-hydrothermal environments (Chiodini, 2009). To this end, significant sustained changes in r_{CH} occurred in 2012 pointing to a steady increase in magmatic component at this time, heralding the 2012-13 period of unrest (Fig. 2). Erratic behaviour in this parameter through 2016, and then again in 2018-19, points to the subtle pressure balance extant between the magmatic source and the enclosing hydrothermal environment. This provides highly valuable insights into subtly changing periods of unrest.

SO_2 is another principle magmatic gas species, and is usually found in conjunction with H_2S in magmatic-hydrothermal environments where the two gases form an important redox buffer (Giggenbach, 1987). SO_2 is highly reactive in the hydrothermal realm, but as a purely magmatic vapour phase, or where the reactivity of SO_2 can otherwise be judged to be constant, the ratio of CO_2/SO_2 (r_{CS}) can be used to identify early stages of magmatic degassing owing to the very different solubilities of the respective gases in melts. CO_2 is much less soluble than SO_2 in melts, hence elevated r_{CS} may herald the arrival new, undegassed magma into the volcanic edifice; Giggenbach, 1996). Ratios of SO_2/CH_4 and H_2S/CH_4, on the other hand, provide further insights into respective inputs of magmatic and hydrothermal end members independent of CO_2, and therefore potentially allow for the discrimination of deep and shallow magmatic degassing, but also the effects of scrubbing of SO_2 by interaction with hydrothermal fluids.

In addition to these gases, temperatures and pressures at two locations in the fumarolic vent will also be monitored. Temperatures will be measured by thermocouple and pressure variations by monitoring back pressures of air being pumped into the vents alongside the thermocouple junctions. In addition, tremor and acoustic sensors will be installed close to the F0 vent. When correlated with campaign style measurement of power outputs from the fumarole (from pitot measurements), these data will allow for real time power output estimates to be made, which will ultimately constrain inverse numerical modelling (iTOUGH2; Finsterle, 2007) of the conduit system at depth. Lastly, wind speed and direction will be logged to assist with interpretation of the acoustic signals from the vent.

Design and Construction of the Field Station

The design brief for the F0 Station was influenced by the following considerations:

- Power consumption: minimise so that it can be run efficiently by solar charging of deep cycle batteries;
- Instrument autonomy: all instrumentation must be able to run in 4 daily duty cycles without human intervention;
- Instrument longevity: The instrumentation should be robust, and capable of running within multiple layers of protective enclosure;

- Station Cost: A balance must be struck between reliability, data quality and economy, all with the understanding that the station could be totally destroyed in a significant eruption event.

The system is comprised of 3 separate modules (Fig. 3), each having its own Campbell (CR6 or CR1000) data logger. The loggers are connected by ethernet, and communicate with one another via Campbell pakbus architecture. A separate power station consisting of solar panels, charging regulator and battery bank provides power to the system. Component parts of each module are packaged in individually sealed containers wherever practicable, and these are in turn contained within heavy duty pelican cases, thus comprising the "module". Robust plywood and timber enclosures house the pelican cases, and offer the first line of defence against ingress of corrosive atmosphere, or indeed ballistics and/or pyroclastic density currents. A new design of enclosure was developed for this installation.

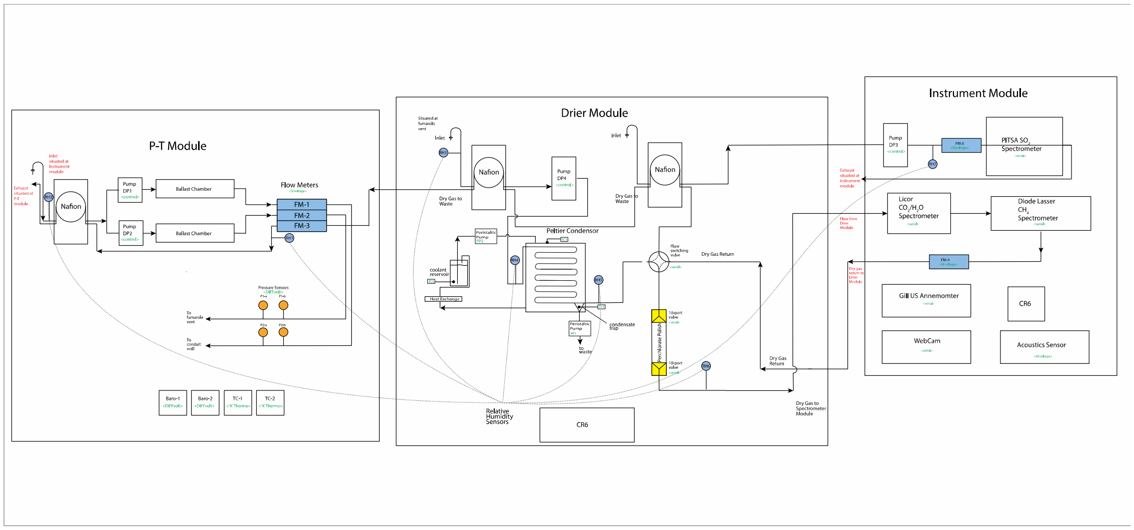


Fig 3. Schematic layout of the 3 main modules of the F0 station.

P-T Module

The P-T Module has two diaphragm pumps in separate channels, both of which draw ambient air in through a common 0.45 mm particulate filter and nafion drier assembly to a T junction, and flow through ballast chambers which are added to remove the pulse-effect of the diaphragm actuation (Fig. 3). The nafion drier receives annular "dry" gas from the Drier Module (discussed below). Gases pass through relative humidity and flow sensors, and then past differential P sensors (in duplicate) en route to the fumarole vent. Ambient air pressure is measured by high precision manometers.

Back pressures and temperatures are monitored at two separate locations in the F0 vent, one at the orifice and the other at a depth of about 1 m below the orifice, the latter requiring augering through the conduit wall. Thermocouples are contained within sealed quartz glass tubes, and positioned alongside identical but unsealed quartz glass tubes which receive flow from the aforementioned diaphragm pumps. Both tubes are sheathed in protective (sacrificial) Ti tubing which aids in insertion of the fragile glass tubes into the conduit/vent flows.

Instrument Module

The instrument module hosts three spectrometers for the analysis of CO_2, CH_4 and SO_2 and also hosts the Gill anemometer and acoustics sensor(s). The SO_2 sensor is a non-dispersive UV absorbance (NDUV) spectrometer built by Ulrich Platt (and students) at Heidelberg University using a UV diode light source. Absorbance features in the 210-230 nm absorbance band allows direct calculation of SO_2 VMR (volume mixing ratio). It has a large dynamic range and very little hysteresis. There is a minor interference with atmospheric ozone in this band, but it is accounted for in the formulation of the detection limit (DL = 0.5 ppm).

The CH_4 sensor is a NDIR multipath laser system produced by West Systems (Italy). It has a detection limit of 0.1 ppmv. The CO_2 sensor is a Licor 870 NDIR spectrometer measuring CO_2 at a wavelength of 4.24 micrometers, and an ancillary channel for measuring water vapor concentration (at 2.595 micrometers).

Drier Module

Condensation of fumarolic water vapour along the flow path will lead to the formation of aggressive, acidic solutions which will cause serious corrosion problems for sensors and valves in the system flow paths. As water vapour is the predominant gas in the discharge, removing it from the high temperature gas stream would tax almost any system designed for this purpose. The Drier Module is therefore designed to remove water vapour from the plume gases which have already cooled and condensed water vapour to ambient atmospheric temperature. Then, via a combination of techniques including permeable membrane extraction, cryo-condensation at 0 °C and desiccant adsorption of remaining water vapour, water is extracted from the inlet gases, taking the condensation temperature well below that of the sensor operating temperatures (< -30 °C).

Incoming plume gases are first exposed to Nafion drier assemblies which consist of a nafion capillary housed in an annulus of Teflon tubing. The nafion material is selectively permeable to water vapour, and provided that there is a difference in chemical potential of water vapour across the membrane, water vapour flows from the moist sample gas into the annulus, and henceforth to waste. To this end, we use a reflux method of pumping the previously dried and analysed gas in the annulus.

For the CO_2 and CH_4 channel (Fig. 3), gases flow from the nafion drier to the condenser. The condenser consists of a serpentine channel machined into a block of hexagonal boron nitride (BN), a compound which is known for its high thermal conductivity and inertness. Two 40 W peltier cells are fixed to the back of the condenser block, with the cold sides facing the BN, and the hot side making contact with a machined, water jacketed block of elemental Cu. Coolant circulates from a 2 L reservoir through the Cu block via a peristaltic pump, and the system is thermostated to maintain temperatures of 0 °C in the BN. Condensate is drained from the trap volume at the end of the serpentine channel via second peristaltic pump.

Relative humidity is measured immediately down-stream of the condenser, before passing into flow control valve 1. If measured values are > 5 ppt, flow is channelled through the annuli of both nafion driers. If < 5 ppt, the valve actuates and flow is directed through the Mg – perchlorate desiccant for final drying (to dew points of ca. ~ -30 °C), and then onward into the Licor CO_2 and CH_4 sensors.

During calibration testing, SO_2 was found to both adsorb onto the Mg-perchlorate and to partially dissolve into the water droplets forming in the condenser. This necessitated separating the SO_2 spectrometer from the combined sensor flow path, and providing this channel a separate pump and nafion drier assembly. This nafion is the first to receive the previously dried gas from the reflux circuit, so thus is the most effective water vapour removal of any of the driers, although the water vapour levels will be higher in this channel that for the CO_2 and CH_4 channels.

Performance

The F0 station was assembled and tested rigorously in Wairakei, and made fully functional, including linkages to InMarSat satellite for data transfer via Scott Technical in Hamilton.

Owing to power demands, we will run the station for a period of 70 minutes every 6 hours, or four 70 minute duty cycles per day. While we will telemeter only sensor and key humidity data back to Wellington, whereas all diagnostic data (flow, temperature, humidity) will be stored locally (SD cards) for troubleshooting purposes should they be required.

Deployment to White Island

Owing to the scale of the operation, the decision was made to Install the power station and A-frame enclosures in October, 2019, in advance of the installation of the instrumentation. Meanwhile, further testing/refinements to the station electronics continued through November, and plans were set around deploying the station during the 2nd week of December (specifically the 11th to the 13th). Unfortunately, the eruption of 9 December 2019 swept the power station and all other enclosures away without a trace. Had the instrumentation been out there at the time, it would have been completely destroyed in the surge associated with the pyroclastic density current.

On a positive note, we still have the working system to hand, and a much better understanding of the demands placed on protective enclosures for the instrumentation at this site. This work will ensue once we are allowed back onto the island and have had a chance to re-evaluate the site and develop new enclosure strategies that are better able to withstand eruptions such as that on 9 December 2019. Our goal is to get this system installed on the island as soon as possible after the ongoing Coronial and Police enquiries are completed, and when it is deemed safe enough to allow GNS staff back onto the island.

Tomographic imaging of active fumarolic environments in the subsurface of White Island

As already mentioned, fumaroles are the pathways of increased permeability along which magmatic and/or hydrothermal vapours travel. They may connect ultimately to magma conduits, or simply discharge hydrothermal vapours which tap fluids on the margins of the magmatic system. Little is actually known of the subsurface phase behaviour of fumarolic environments, apart from the fact that they consist of either single phase vapour or two-phase vapour-liquid regions at their core, and are surrounded in turn by single phase liquid at some lateral distance from the conduit (e.g., Stevenson, 1993). It is also perceived that the environments are responsive to changing heat and mass transport, and have been described as “self-adjusting” (e.g., Giggenbach, 1987), although knowledge around the scale of these environments and processes is unclear.

Recent advances around the application of resistive tomography show promise for imaging regions of high vapour saturation in hydrothermal environments (e.g., at Solfatara; Gresse et al., 2017; Gresse et al., 2018) such as those expected to be inherent to fumarolic conduits. The principle is based on an anticipated conductivity contrast between highly conductive single phase liquid regions, versus lower conductivities of vapour-static environments. This was well demonstrated for the Solfatara geothermal system at Campi Flegrei, but its applicability to active volcanoes, especially those with higher salinity fluids such as at White Island, has remained untested until now.

In the attached manuscript we present inverse models of Electrical Resistivity Tomography (ERT) measurements of the Whakaari/White Island, New Zealand, hydrothermal system made around fumarole `F0' in January 2019. We constrain the interpretation of ERT tomograms using published rock matrix electrical properties (Heap et al., 2017a; Ghorbani et al., 2018) and measurements of liquid pH and conductivity. Insights into the physical state of the F0 fumarolic conduit, and likely processes that are affecting its behaviour at depth, can be deduced from time series volcanic emission rate data for the volcano and from physicochemical parameters of the fumarolic gases themselves. Here we have considered time series data for the period March 2018 to August 2019 in order to provide constraints on the dynamic processes that were affecting the conduit system at the time of the ERT survey, which is effectively a “snapshot" in time of the hydrothermal system, some 11 months before the deadly eruption of 9 December 2019.

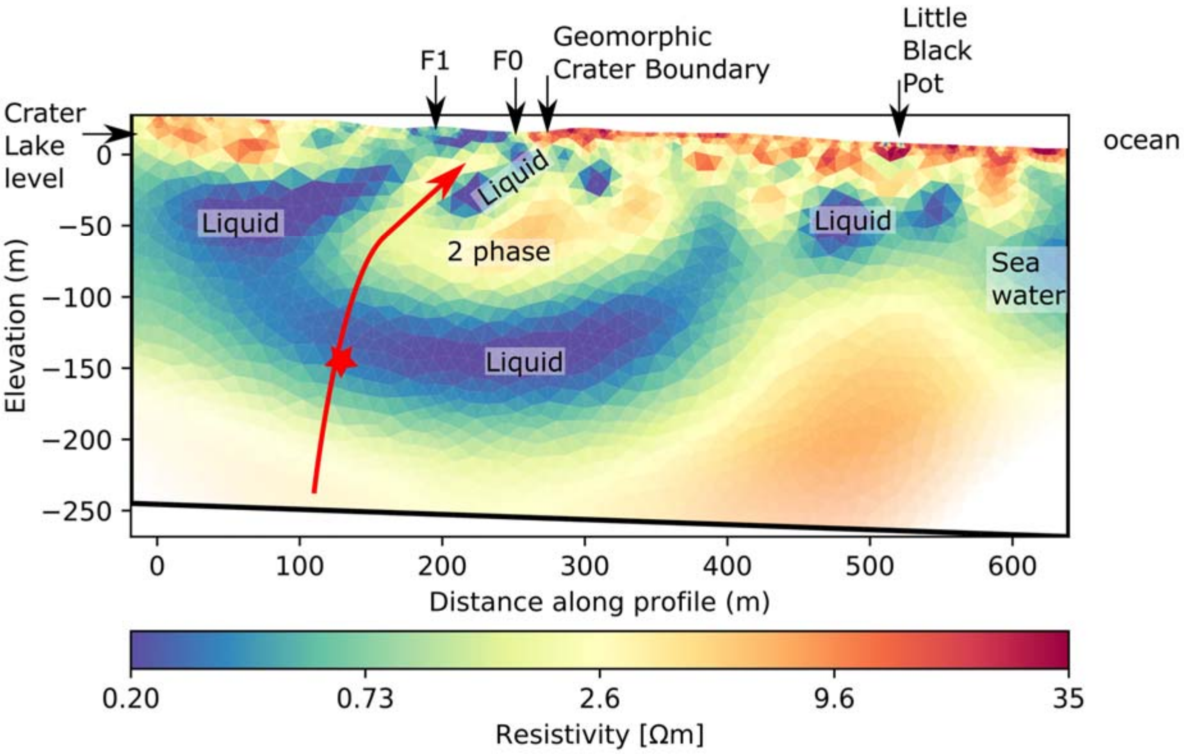


Figure 4. Interpretation of resistivity section showing distribution of single-phase liquid and two-phase regions. Degree of liquid saturation will vary along a continuum controlled by temperature and pressure and influenced by rock porosity and permeability. The red arrow indicates the proposed fumarole F0 conduit projected onto the ERT section plane. The red star is the location of the deformation source from Fournier and Chardot (2012). The location of the geomorphic crater boundary and other surface features are labelled.

Detailed analysis of electrical resistivity tomograms is aided by an extensive data set of rock and fluid physical properties that together with a fumarolic and airborne gas composition timeseries provides a detailed snapshot of the White Island hydrothermal - magmatic system in the year prior to the 9 December 2019 eruption. The availability of detailed rock electrical properties for White Island, together with a new dataset of pore liquid conductivities, allows us to focus our interpretation on the degree of saturation of the pore space, taking into account the fact that the surface conductivity is low. ERT has imaged a very low resistivity environment, < 1 ohm.m, representing pore space filled with conductive liquids whose conductivity is enhanced through their very low (<1) pH. Imaging acid filled pore space is important for identifying areas of hydrothermally weakened rock that are susceptible to landslide and failure, important hazards to consider on steep sided volcanic flanks.

Within this saturated, conductive, acidic environment is a narrow, steeply dipping 2-5 m diameter feature beneath the fumarole area. We interpret this feature as a two-phase zone consisting of pore space at irreducible or residual liquid saturation (Sw = 0.05 to 0.2) and predominantly lower temperature gases equilibrated with the hydrothermal environment with some higher temperature gases equilibrated within the magmatic environment. The fumarole conduit is surrounded by pore space saturated with a cooler liquid phase fluid of similar conductivity to liquid condensate pools found adjacent to the fumaroles. The piezometric surface of the crater lake fluid impinges on the fumarole conduit showing direct evidence of the role the crater lake has in controlling the fumarole dynamics. The complex distribution of two-phase vapour-liquid and single-phase liquid around fumarole F0 suggests lithology, alteration and permeability are also likely important governing factors alongside the temperature and pressure gradients in the fumarole.

This survey occurred at a time when the fumarolic temperatures were near the low end of the temperature range (Fig. 2), which provides a good benchmark for future characterisation(s) of the conduit phase state via electrical resistive tomography. All in all, this was a highly successful, proof of concept that ERT imaging surveys can be done on active volcanoes, including even those which have high salinity and low pH fluids such as that at White Island. This is quite a stunning result which can be applied globally.

Development of forward numerical models of a fumaroles

A series of generic TOUGH2 (Pruess, 1991) models with radial symmetry consisting of a permeable conduit at its centre have been constructed to explore various factors that affect fumarolic conduit environments at depth.

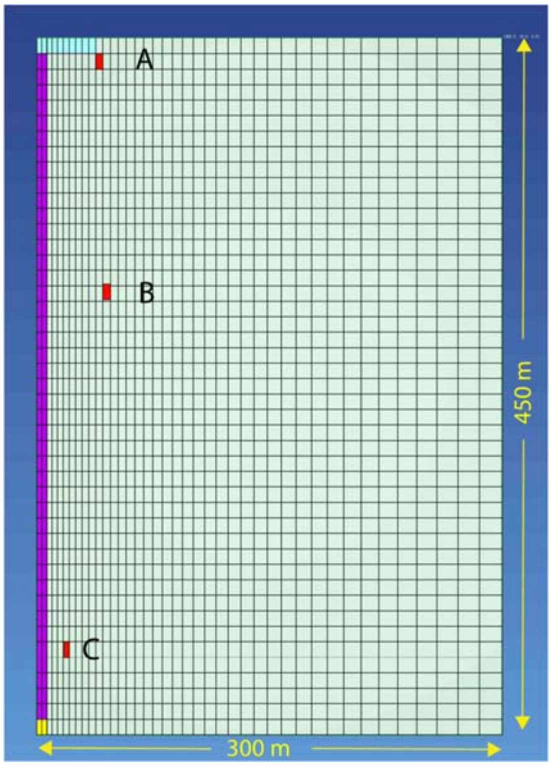
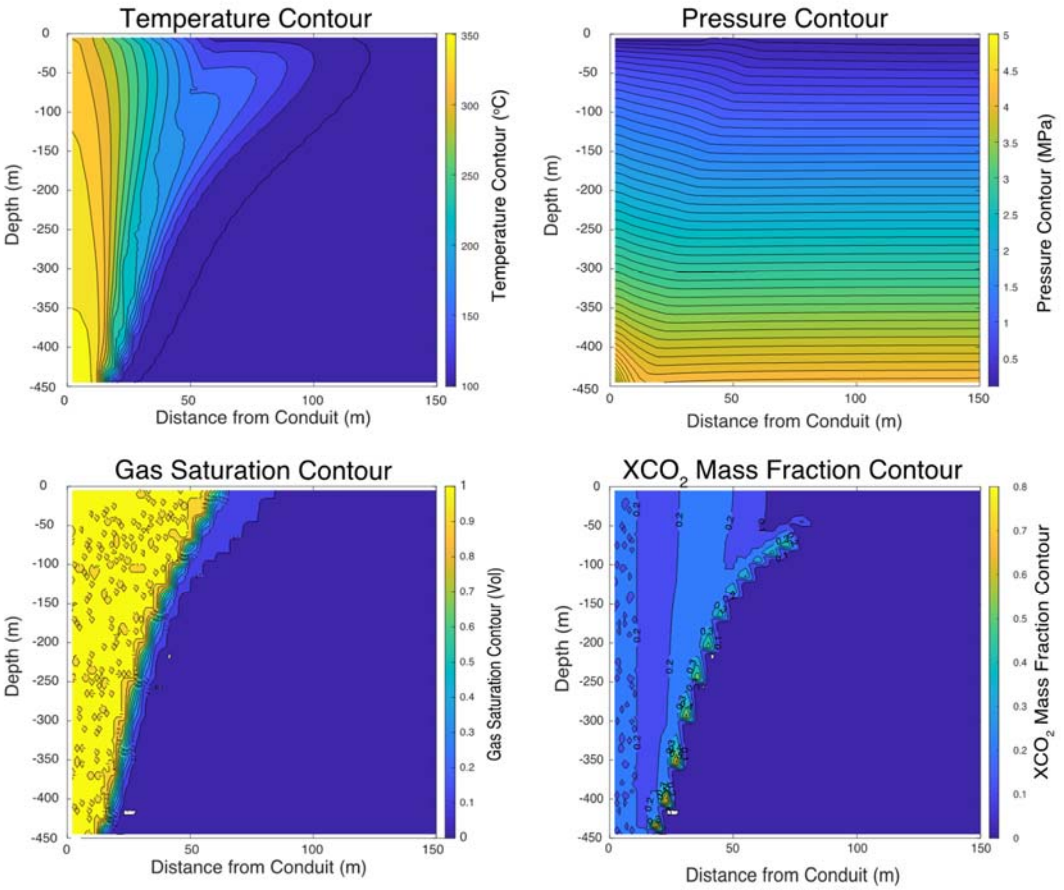


Fig. 5. TOUGH2 mesh for fumarolic conduit system. Radial symmetry around conduit elements (in purple), with source elements at 450 m depth (in yellow).

An example mesh and output results are shown in Fig.5. The grid is 300 m wide and 450 m deep and is comprised of 45 elements along the z axis, at 10 m intervals. There are 40 elements along the x axis, scaled by a factor of 1.04 which provides finer structure in the centre of the block. Lateral permeability is everywhere set at 1E-13 m^2, whereas vertical permeability is 1E-12 m^2 in the mesh, and the central two elements are set to 1E-11m^2, constituting a higher permeability conduit (purple coloured elements in Fig.5). A small lake is shown occupying the central 10 elements, and a single atmospheric block overlies the radial mesh. All elements in the model have initial liquid temperatures of 99 °C.

The bottom two elements in the conduit serve as the source of heat and mass, through which flow 8 kg/s of steam and 2 kg/s of CO_2 with enthalpies of 3E6 and 8E5 J/kg respectively. After a model period of 5 years, temperatures in the conduit and adjacent elements have risen to ~ 350 °C in the source elements, whereas steam and CO_2 discharging through what once was the lake bed are ~ 250 °C (Fig. 6). Pressures in the conduit are elevated above hydrostatic, and fan outwards with decreasing depth, denoting a convective flow regime in the model space. The entire conduit and adjacent enclosing elements are close to single-phase vapour by the end of the period, but the transition from single phase liquid to vapour occurs over a relatively short interval of 10 to 20 m from the conduit. CO_2 mass fraction in the conduit is largely that of the source fluid, whereas slightly elevated values are found in the transitional zone to single phase liquid.

Fig. 6. Contour plots denoting temperature, pressure, gas saturation and CO_2 mass fraction after a simulation time of 5 years.



White Island is a pulsatory emitter of volcanic gas (e.g., Christenson et al., 2017; Werner et al., 2007), with CO_2 emissions ranging between 377 to 3110 T/d over the period 2003 to 2016. The impact of such variations on fumarolic environments is readily modelled by TOUGH2 (Fig. 7).

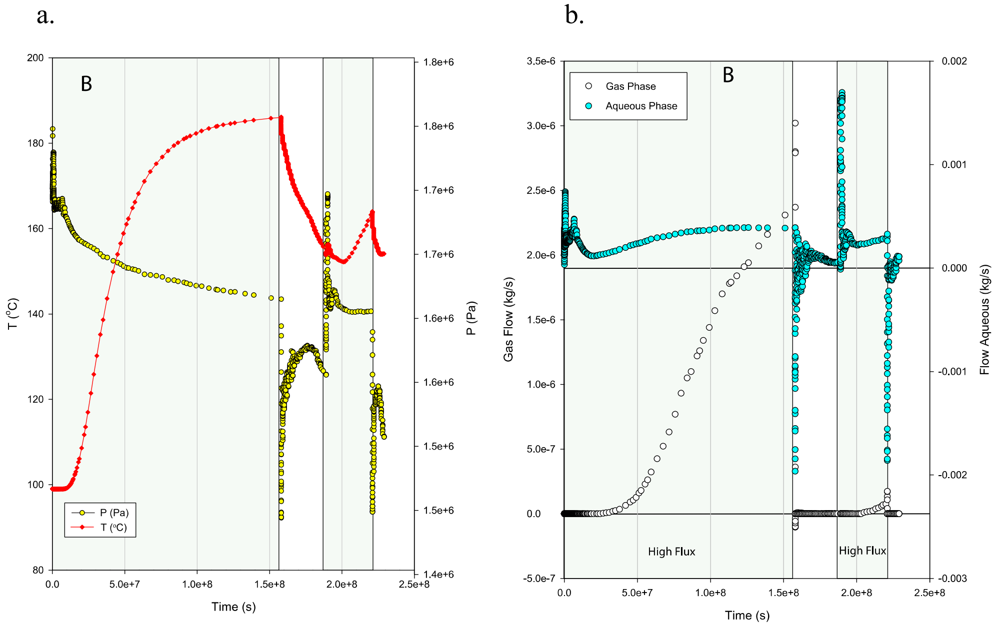


Fig. 7. Time series plot of temperature and pressure (a.) and water and gas movement (b.) as functions of varying source inputs. Green shaded areas represent the periods where 8 kg/s and 2 kg/s of H_2O and CO_2, respectively, are injected at the source elements, whereas white regions denote reductions to 25 % of the original values.

Here we investigate the physical impact of decreasing the source inputs by a factor of 4 on fluid situated at location B in the mesh (Fig. 5). During initial heating, temperatures within this element increase to ca. 185 °C during the initial five year period, whereas pressures slowly decline owing to the development of 2-phase vapour-liquid conditions in the element. Reduction of source inputs immediately imposes a pressure transient of some 1.5E5 Pa at point B (Fig. 7a), and a sustained decline in temperature in this element ensues. Interestingly, liquid and vapour phase motion along the x direction were initially away from the conduit (positive values of flow), but the liquid phase rapidly reverses flow toward the conduit as a result of the transient, and vapour ceases to flow altogether until the next period of high flux is re-established. Such events have large impacts on both the chemical and physical attributes of the fumarolic emission.

This relatively simple demonstration of the effects of pressure transients on the system resulting from changes in unrest (varying source inputs) points to the dynamic behaviour of the magma-hydrothermal interface, and how monitoring the physico-chemical behaviour of the fumarolic emissions will provide strong insights into processes operating at depth. Ultimately, inverse modelling of these processes has the potential to become a highly useful tool, perhaps as part of an AI approach to understanding state variables in the subsurface environment.

Impact

Aspects of this study are the "first of their kind" on several fronts, and the work therefore defines a major step forward in our quest to enhance the autonomous monitoring of active volcanoes worldwide. The need for such systems as presented here is clearly underscored by the 9 December 2019 eruption of White Island Whakaari, which occurred without warning. There is a clear need to extract more information/data from these volcanoes if we are to fully understand the hazards they present, and be in a position to forecast such events, not to mention that at elevated unrest will preclude landing people on the island for data gathering purposes

To this point, our geochemical monitoring practises, and indeed those of other Volcanic Observatories around the world, have few if any real time geochemical monitoring systems installed on active volcanoes. Typically, SO_2 emission is measured spectroscopically in volcanic plumes, and emission rates can be estimated from those measurements. In some instances, these data are combined with so-called multi-gas instruments which record CO_2, SO_2 and H_2S, and where possible these results are combined to inform on C/S ratios. However, these instruments are not without their shortcomings and the insights afforded are often ambiguous, as signals can derive from multiple sources or be adversely affected by meteorological conditions.

The facility that is described herewith is hopefully the first of many comprehensive, high quality fumarolic data stations to come; as technology improves, so too will the ability to instrument individual fumaroles in ways that are even more comprehensive and cost effective than those described herein.

Future work

The next steps for this co-funded project is to get the systems described here finally operational at White Island. It then becomes a matter of:

- Merging data from the F0 station to all other observables from the island
- Derive constraints for the forward heat and mass transport model of this feature from the data
- Using these constraints to model the reactive transport of such fumarolic environments
- Develop an inverse heat and mass transport model of Fumarole F0

Acknowledgements

Many people and organisations have contributed to this undertaking:

- This work would not have been possible without the EQC Biennial Grant scheme which partially underwrote capital expenditure for various components of the F0 station, but also supported the Electrical Resistive Tomography study of the crater floor at White Island and a portion of the numerical model development.
- MBIE Hazards Research Platform Funding has ongoing support for work that underpins all aspects of this project through the Volcanic Processes Project
- GeoNet, principally Dr Ken Gledhill, who supported various aspects of this project in the design phase.
- Prof. Ulrich Platt, University of Heidelberg. A brief brainstorm with Ulrich at a volcanic gas workshop in the Atacama Desert of Chile around the concept of building a NDUV spectrometer for measuring SO_2, led to the creation of the exquisite SO_2 sensor that now resides in the Instrument Module of the F0 station.
- Richard Johnson and Bruce Cruthers, both from GNS, brought a wealth of electronics know-how to the effort, as well as experience with packaging of those electronics into field/corrosion-resistant systems for deployment on White Island

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Links to publications/theses
n/a

List of key end users
Potential end users of output from such autonomous stations include:

GNS Science, Volcanic Monitoring Group

Dept. Conservation,

District Councils

NEMA

Police

Various overseas volcano observatories