Supplementary Material

Bayesian Network modeling and expert elicitation for probabilistic eruption forecasting: pilot study for Whakaari / White Island, New Zealand

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1 Summary

In this supplementary material, we present details on the overall method followed in our pilot study. We also provide information that was used during the model quantification, including workshop notes, the questionnaire to elicit the conditional probabilities, and the feedback questionnaire.

2 Method for the pilot study

The overall method for the pilot study was embedded in principles of risk assessment (Gerstenberger and Christophersen, 2016). Following a project initiation phase, we used the four-step procedure of: (1) establishing the context; (2) developing the model structure; (3) quantifying the model, and (4) completion. Figure S1 illustrates the workflow.

2.1 Project initiation

During the project initiation phase, we assembled an initial team covering a wide range of expertise, decided on the problem to address, and explored modeling options. The initial team members had informal discussions about BNs, volcano monitoring data and volcanic hazards that could lead to fatalities. They concluded that the type and size of eruption are important variables for determining the risk of fatality. They decided to focus on eruptions first (as opposed to fatalities), with the expectation that nodes could either be later added to the BN or a separate BN model could be developed assuming an eruption. The team explored different dependency options as illustrated in Figure 1 of the main manuscript. Around that time the retrospective analysis of the 1975-77 volcanic crisis at La Soufrière volcano, Guadeloupe was published (Hincks et al., 2014). The initial team decided to adapt the La Soufrière model structure for Whakaari as a first pilot model for New Zealand.

2.2 Establishing the context

Establishing the context is important for any risk assessment (IEC/ISO, 2009; Gerstenberger et al., 2013). This includes clearly defining the risk question, identifying stakeholders, selecting experts and choosing appropriate tools (Figure S1).

The question to be addressed by the BN was finalized as "what is the probability of an eruption at Whakaari in the next month that would impact beyond the crater rim of the 1976 – 2000 crater complex?". This is consistent with the question for the regular elicitation of eruption probabilities for Whakaari (Deligne et al., 2018).

Stakeholders for volcanic eruption forecasts can include a wide and diverse range of groups and individuals. Within the context of this pilot study, the key stakeholders were the members of the volcano monitoring team assessing the usefulness of BN modeling in their daily work. Best practice entails involving stakeholders in the risk assessment procedure (IEC/ISO, 2009). Here, monitoring team members participated in all stages of the process. The head of the volcanology department, who is also the volcano monitoring team leader, was the official project owner.

We solicited feedback on the initial model adaptation from senior team members of different sub-disciplines. For the model quantification we opened participation to all team members. We also invited university-based New Zealand volcanologists to include external feedback, as diverse groups of people have been found to perform better than homogeneous groups (e.g. Hong and Page, 2004; Bang and Frith, 2017).

There are various commercial software solutions available for discrete BNs. We worked interchangeably with Netica (Norsys, 1995-2018) and GeNie (BayesFusion, 2018). For the analysis of the data provided by the experts we used the statistical software R (R Development Core Team, 2008), in particular the BN modeling package gRain (Højsgaard, 2012).

2.3 Developing the model structure

Model structure development was iterative and involved defining the variables and their interdependencies. The aims of the model development were (1) to find a parsimonious representation of the hidden volcanic processes consistent with the conceptual understanding of the volcanic processes at Whakaari and (2) to capture all regularly measured observations that provide insight into a possible future eruption. To reduce the elicitation burden we described each variable with only two states, “yes” and “no”.

The initial team modified the structure of the La Soufrière model based on informal discussions with individuals from the volcano monitoring team. We quickly ascertained that individuals from different sub-disciplines had different understandings of the driving processes. Subsequently, in one particularly successful two-hour meeting we discussed the model structure jointly with experts from seismology, geochemistry, geodesy and general geophysics. In fact, presenting the BN framework allowed the different understandings of the volcanic processes to be discussed in an insightful way. Ideally there would have been another similar meeting to finalize the model prior to quantification at the workshop.

Clearly defining the nodes and states is important part of the model development: this ensures that experts share a common understanding of the elicitation questions. The nodes for the internal processes and the eruptions were defined consistently, albeit vague. Experts were very reluctant to set thresholds to define the “yes” and “no” state because they felt that two states could not adequately represent the range of observations. More sophisticated modeling options were outside the scope of the pilot project. For the pilot project, experts were happy to answer based on the threshold they had in mind when estimating the probabilities. Consequently, we effectively have 11 different BN models. It is challenging to do any analysis that include the observational nodes.

2.4 Quantifying the model

The third step of our risk assessment method ‘Quantifying the model’ has three components: preparing the expert elicitation workshop, the elicitation workshop and combining the assessment. Quantifying a discrete BN requires estimating the mass function for the nodes that have no parents and the conditional probability tables for child nodes. We used structured expert judgment to quantify our model in a workshop-style setting. We held a workshop over two half days in early December 2015. Below we describe each component in more detail than possible in the main manuscript.

2.4.1 Preparing the expert elicitation workshop

Preparing the workshop includes the ethics considerations, preparation of the questionnaires and logistics. We followed the Massey University Code of Ethical Conduct (http://www.massey.ac.nz/massey/research/research-ethics/human-ethics/code-ethical-conduct.cfm). We discussed the research and the associated ethical issues with social scientist Dr Sally Potter. We ensured that processes were in place to keep confidential the results of the originally planned calibration exercise. We evaluated the project to be of low-risk of harm to the participants. Consequently, we submitted a Low Risk Notification.

For the workshop, we prepared notes to describe the BN and introductory presentations on BN modeling and expert elicitation. An experienced team member of the volcano monitoring team helped with the workshop notes, which were reviewed by two further team members and are appended to this document. The questionnaire to elicit the probabilities for the BN was prepared as an electronic online version in Survey Monkey, but paper copies also available. An additional questionnaire was prepared to gather feedback on the workshop, interest in BN modeling and the perception of the expert elicitation model; it was amended during the workshop incorporating suggestions from the experts, e.g. to add self-weighting of expertise in the different areas of the BN. Both questionnaires are appended to this document.

2.4.2 Elicitation workshop

The two half-day workshop was held in December 2015 and facilitated by project leader. It involved 11 experts and a guest speaker on expert elicitation. About half of the experts had been involved in the model development in some way and the other half was completely new to BN modeling. Seven experts and the facilitator attended the workshop at the GNS Science office in Wairakei: Agnes Mazot, Brad Scott, Geoff Kilgour, Lauriane Chardot, Nico Fournier, Steve Sherburn, all members of the volcano monitoring team at GNS Science, and Associate Professor Jon Procter of Massey University. Three experts were in the GNS Science Avalon office connected through a video link: Art Jolly, Natalia Deligne and Tony Hurst, all members of the volcano monitoring team at GNS Science. The presenter on structured expert judgment, Matt Gerstenberger, joined the Avalon group at the beginning of the meeting. Associate Professor Jan Marie Lindsay from the University of Auckland joined the workshop via Skype. The communication across the three sites worked well despite prior concerns with a multi-location workshop.

The workshop followed principles of structured expert judgment. It started with two short presentations. The first was an introduction on BN modeling given by the project leader, which included a demonstration of the BN for La Soufrière. This allowed experts who were new to BN modeling to see a working model in action and get a feel of what we were trying to achieve. The second presentation was an introduction to structured expert judgment given by a colleague external to the project. Following the presentations, one member of the volcano monitoring team facilitated an exercise with some sample calibration questions that were filled in anomalously and were not used for weighting. The purpose of the exercise was twofold: (1) to introduce the experts to the concepts of calibration questions and (2) familiarize the experts with estimating probabilities and their uncertainties. Unfortunately, the project did not have the resources to develop topic specific calibration question to weight the experts.

For each of the four areas of the BN there were discussions followed by time for the experts to estimate the required probabilities. The workshop was interactive: we were able to integrate feedback and requests that came up during the discussion. For example, one expert proposed an additional node on observing fresh glass. We added a node and connected it up to the driving processes as the experts saw most fitting. The elicitation questions for this node were added to the feedback questionnaire that was filled in at the end of the workshop.

During the workshop participants proposed to give themselves a weight according to their confidence in their knowledge in the different areas of the BN. This weighting was also included in the feedback questionnaire. The experts scored their own knowledge in the four areas of the BN from 1 (not very confident) to 10 (very confident). We calculated two weights from the data. Weight 1 values each expert the same, i.e. we first normalize the contribution of each expert and then normalize all experts' contribution for each area. Weight 2 takes each expert's self-assessment and only normalizes all experts' contribution for each area. The sums of the self-assessments range from 17 to 30, reflecting that some experts were generally more confident in their knowledge than others. Thus, in the second weighting scheme, the most-contributing expert has 1.76 times more weight than the least-contributing expert.

Discussions during the workshops addressed whether all elicitation data could be made available or whether there were concerns about any aspect. This question was repeated in the feedback questionnaire. No experts had reservation about sharing the data and making comments available.

2.4.3 Combining the assessments

Combining the assessments involved processing of the questionnaires and communicating the results. If we had used calibration questions, we would have evaluated them at this time.

Processing the questionnaires included inputting all quantitative answers into a consistent electronic format, plotting the raw answers, and calculating the BN probabilities and their uncertainties. The quantitative analysis was done in the statistical programming language R that also has good graphics packages for plotting data. Qualitative answers were evaluated separately.

The initial analysis began with checking the questionnaire completeness. Unfortunately, one feedback questionnaire was lost, and the information could not be retrieved. Some experts provided their conditional probability estimates electronically. For the other elicitation questionnaires, we had administrative support for data entry. We checked for inconsistencies, for example, flagging if the best estimate lied outside the range of the 10th and 90th percentile. Issues were followed up with the individual participant and corrected.

For further data processing and insuring anonymity, the project leader randomly assigned a number to each expert. The expert number stayed the same for all probability estimates as well as the description of the states. Thus, it is possible to trace individual answers and see their effect on the preliminary results (Christophersen, 2017).

The first analysis consisted of plotting all probabilities and their uncertainties. There are a total of 120 individual figures for each of the probability questions featuring the best estimates and uncertainties of the eleven experts, as well as the averaged and two weighted answers (Christophersen, 2017). Examples of these are shown in Figure 6 of the main manuscript. We used the R package "gRain" to analyze the BN (Højsgaard, 2012). The uncertainty estimates for each answer by each expert were used to estimate the parameters of a beta distribution, for each probability estimate and for the combined answers: a total of 1,680 beta distributions (120 x 14) were estimated. Each distribution was sampled 1000 times and combined to calculate uncertainties for each node. In total, 14,000 BN models were calculated; 1000 for each expert and for the three ways of combining all experts.

The qualitative comments on BN modeling and expert elicitation, and feedback on the workshop, were analyzed separately. Experts were randomly assigned the letters A – K so that comments that might identify individuals are not traceable to the quantitative answers. All comments can be viewed (Christophersen, 2017) and a summary is available in the manuscript in section '***Other findings from the workshop'***.

Communicating preliminary results and collecting feedback from the experts on the outcome is an important part of a structured expert elicitation process (Gerstenberger and Christophersen, 2016). All experts' answers were collated into a report (Christophersen, 2017), and a draft version was distributed to all experts in April 2016. Given the wealth of material, only a few experts were able to read everything and ponder the results. The project leader and leader of the volcano monitoring team organized a follow-up videoconference in August 2016, with 5 experts in Wairakei and 4 experts in Avalon. The university experts were invited but were unable to attend. There was insufficient time to discuss the results in detail, rather, we had a general discussion of the overall forecast of the BN. The experts also discussed how an April 2016 eruption fitted the BN model. There was a particular focus on one node, "N4: Presence of a hydrothermal system seal". Following that meeting, the project leader and team leader of the volcano monitoring team decided to organize a follow-up elicitation by questionnaire that was conditioned on the situation at White Island at the time., but only two experts returned the questionnaire. These were not processed further.

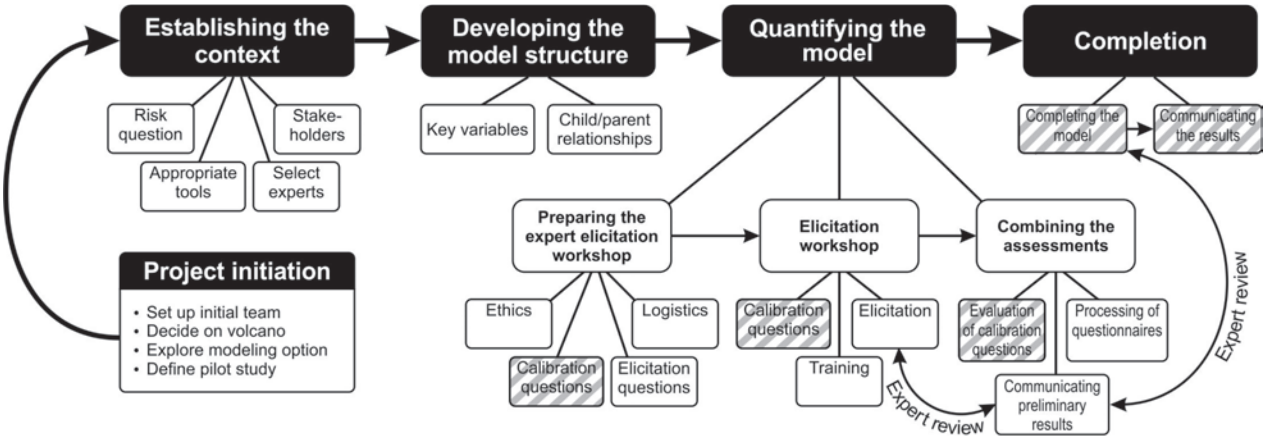
Ideally we would have conducted an expert calibration (Cooke, 1991), but found it challenging to develop suitable calibration questions that were similar in nature to the target questions. We were guided by previous experiences (Gerstenberger et al., 2014; Gerstenberger and Christophersen, 2016), where experts struggled to see the relevance of the calibration questions with respect to the target question. We wanted to avoid discussion about appropriateness of individual calibration question and instead focus the limited time on the BN modeling. We had access to general questions used in previous calibrations, e.g. the ones used in Montserrat (Wadge and Aspinall, 2014). We chose a few example questions to train the experts on estimating of quantiles and provide a flavor of the calibration exercise.

2.5 Logistics and time requirements

Time requirements for model development were modest. It took a two-hour meeting for the initial team to adapt the La Soufrière model to Whakaari and two further hours to draft the initial set of elicitation questions. Ideally there would have been two to three two-hour meetings with a small group of experts from different sub-disciplines to review and fine-tune sub-networks for the overall model.

The logistical effort involved in planning the workshop likewise did not require much time. The expert elicitation workshop ran for two half-days. The most time-consuming aspect was the analysis of the data, which took three to four weeks. This would be much less onerous for a smaller BN.

Figure S1 A flow-chart of the risk assessment method used during the pilot study to develop a Bayesian network with expert elicitation. The four key steps in the black boxes at the top were preceded by a project initiation phase specific to our pilot study. The shaded boxes indicate tasks that are part of the method but were not completed during the pilot study.



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4 Appended to this document are:

The consent form for participants at the workshop (3 pages)

The workshop notes (9 pages)

Elicitation questionnaire (28 pages)

Feedback questionnaire (6 pages)

Participant Information and Consent Form

Probabilistically forecasting eruptions on White Island volcano using Bayesian Networks (BNs) and Structured Expert Elicitation (SEE)

Please take the time to read the following information carefully, and consider whether you would be willing to take part in the expert elicitation workshop.

Research aim:

The main aim of this research is to explore whether Bayesian Network modelling can be a useful decision support tool for volcanic monitoring in New Zealand. We further investigate methodological questions of structured expert elicitation. The aim of the workshop is to elicit probabilities for the Bayesian Network as explained further below.

Bayesian Network (BN) modelling:

BNs provide a framework to model complex systems, and are used in a wide range of sectors (e.g., for modelling water pipe failures and assessing biosecurity risks). Each variable in the system (e.g., the 'number of volcano-tectonic earthquakes') is described by a 'node' in the model, and each node has various 'states' (e.g., 'low', 'moderate' and 'high'). Behind each node is a conditional probability table which quantifies relationships between the variables. Those probability tables need to be filled in to model our understanding of the interdependencies. This will be further explained during the workshop.

BNs have been applied in volcanology elsewhere before (e.g. retrospectively for Guadeloupe[1]) and we want to investigate their usefulness in volcanic monitoring in New Zealand. We have chosen White Island as a test case and have developed the structure of a BN to forecast eruptions within a one month time period. The next step in the model development is a workshop to elicit the probabilities for the conditional probability tables.

Structured Expert Elicitation (SEE):

SEE is a method to use expert knowledge when data are scarce; its use is well established in volcanology through the on-going Montserrat elicitation[2]. In our case, the SEE will involve asking the participating experts about 10-15 calibration questions. These questions will be similar to the 'target questions' that we will need to answer to fill in the conditional probability tables for the White Island BN. The experts provide their answers and uncertainty estimates, which will both be used to weight answers to the target questions.

We will collaborate with Ellie Scourse, a PhD student at the University of Bristol, U.K., who is supervised by volcanologists Steven Sparks and Willy Aspinall. With Willy's support, Ellie will design the calibration questions for our workshop. Ellie will receive the answers to the calibration questionnaire using a coding system, so she won't know who said what. She will undertake different sensitivity analyses and publish the results in the context of what makes a good calibration question. This will help us in future work involving SEE, and it will help us understand how sensitive the answers are depending on combining the experts' answers is different ways.

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[1] Hincks, T.K.; Komorowski, J.C.; Sparks, S.R.; Aspinall, W.P. 2014. Retrospective analysis of uncertain eruption precursors at La Soufrière volcano, Guadeloupe, 1975–77: volcanic hazard assessment using a Bayesian Belief Network approach. *Journal of Applied Volcanology 3(1):* 1-26.

[2] Aspinall, W. 2010. A route to more tractable expert advice. *Nature 463(7279):* 294-295.

Due to the potential risk of perceived reputation damage, or to participants' self-confidence during the weighting of experts in this type of procedure, we will take great care to ensure that results of the weighting cannot be traced back to any individual.

The workshop participants

The participants in this workshop are members of the GeoNet volcanic monitoring team, and scientists from several universities who have a good understanding of volcanic processes.

What does the workshop involve?

The workshop will run over two half days on 3rd and 4th December 2015. We are likely to hold the workshop at the GNS offices in Wairakei as well as Avalon, connected by video link, with most people likely to be in Wairakei. On Thursday we will start at 1 pm and run until 5:00 pm and on Friday we start at 9 am and finish by 1 pm. We are happy to organise accommodation and transport for external participants. Please contact Annemarie for this.

The workshop will start with an introduction to the project, followed by a brief introduction to structured expert elicitation. The experts will fill in the calibration questionnaire individually, and will hand them to the facilitators (Dr Annemarie Christophersen and Dr Sally Potter). Ellie and Annemarie will process the data overnight. For training purposes on uncertainty estimates, the answers to the calibration questions will be presented on the second day, along with how the group answered them. Again, individual answers by participants will not be traceable.

The main focus of the workshop is on discussing the Bayesian Network to forecast eruptions on White Island. Following group discussions on the variables, each expert will fill in their own answers to the questions that quantify the conditional probability tables. At the end there will be a brief general discussion on the workshop experience with particular focus on the calibration questions.

Participant rights

Whilst your contribution would be most appreciated, **you are under no obligation to participate in this research**. Following the Massey University Code of Ethical Conduct, if you choose to participate:

- your answers to any question will be anonymous at all times, including in any published results
- you may decline to answer any questions
- you may withdraw from the study at any time
- you may ask any questions about the study
- you will be given access to a summary of the project findings when it is concluded.

Data storage

Data collected will consist of (1) the calibration questionnaire (hard-copy), (2) assessment of the conditional probability tables (ideally electronically), (3) a brief questionnaire on the experience with the calibration questions (most likely hard copy), and (4) notes of the discussion. The calibration questionnaires will be stored by the research leader (Annemarie). No other person will have access to these data, aside from Ellie, who will have the coded (anonymised) data. The assessment of the conditional probability tables will be weighted in different ways and the aggregated group results available to the whole research team, as well as the participants. At the conclusion of the research, the data will be stored in a secure location at GNS Science, Lower Hutt, New Zealand. Ellie Scourse will manage the data collected for the investigation of what makes a good calibration question (3 and 4 above).

Information about the researchers

Dr Annemarie Christophersen, Hazard and Risk Scientist, leads the project in consultation with Dr Art Jolly and Dr Nico Fournier. Ellie's component of the research is supervised by Professor Willy Aspinall. Dr Sally Potter is assisting with the facilitation, ethics, and social science aspects. If you have questions about the research being undertaken, please feel free to contact Annemarie

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Consent to participate in the workshop on Probabilistically forecasting eruptions on White Island volcano using Bayesian Networks (BNs) and Structured Expert Elicitation (SEE)

If you have read the information on the previous page and are willing to participate in this research, please fill in the details below:	
Please print your name:	Date: / /
Position/role:	
Signature:	
You have the right to decline to answer any particular question.	

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director (Research Ethics), telephone 06 356 9099, extn 86015, or email humanethics@massey.ac.nz.

Description of White Island Bayesian Network (BN)

The White Island BN is a first attempt to explore BN modelling as a decision support tool to probabilistically forecast volcanic eruptions in New Zealand. We have developed a BN model for White Island that simplifies the assessment of volcanic processes that lead to eruption to only four nodes (yellow ovals in Figures 1 – 4). The volcanic processes can lead to three types of eruptions (orange ovals in Figure 1) and they also cause various observables (blue ovals in Figures 2, 3 and 5). We have purposefully kept the BN model simple so that it hopefully satisfies different conceptual models that people may have.

To keep things simple in our first BN, each node in the White Island BN has only two states "yes" and "no". Since the probabilities for all states have to add to 100% and we only have two states, we only ask the question for the "yes" state. Once we have the model fully quantified, we can do different sensitivity analyses that will help us understand which nodes are particularly important and may warrant additional states.

Behind each node sits a conditional probability table that quantifies the probability of "yes" and "no" for all different possible combinations of parent states. The purpose of the workshop is to answer all questions necessary to populate the conditional probability tables.

During the workshop we have no time to change the current model. However, at the end of the workshop we will be asking for feedback to improve the model. There will be a chance to discuss how else BNs may be useful and what other questions they could address. Below we list some key feature of the White Island BN before describing it node by node.

Features of the White Island BN

- The aim of the model is to forecast the probability of volcanic eruption within the next month[1]. This time frame is consistent with current elicitation at volcanic alert level (VAL) 2.
- Since we are interested in the probability of eruption within the next month, we also consider the volcanic processes node for a one-month duration. For example for node N1: What is the probability of gas rich magma ascending in any one-month period? Moving to a child node of N1, we consider conditions of "yes" or "no" magma ascending at the current time including any time in the previous month and regardless of how long this process may take or has been on-going. Thus one question for Node 3 is "Given that there is "Gas rich magma is ascending" and there is "Shallow magma", what is the probability of "Magmatic perturbation of the hydrothermal system" within a one-month period?"
- In our node definitions we use the terms "high", "increase" and "elevated" to express an increase in level of volcanic activity. We use the terms "recent" and "extended durations" to refer to volcanic activity in time. We will discuss the meaning of those terms during the workshop, and may not necessarily reach an agreement on a definition. That's ok. We will ask each participant to define their own understanding of the terms when answering the BN questions.
- We separate the BN model into four different areas:
    1. The volcanic processes leading to eruption
    2. Observations related to seismicity
    3. Geophysical and surface observations
    4. Observations related to geochemistry.

[1] Please note that "one month" refers to a four week period consistent with the elicitations undertaken by the volcano monitoring team.

- During the workshop we will discuss one area at a time, and then each participant has time to individually answer the questions to quantify the conditional probability tables.

The volcanic processes leading to eruption

Figure 1 shows the four (yellow) nodes that describe the magmatic processes at White Island volcano and lead to eruption (orange nodes 5-6). The arrows in Figure 1 describe the dependencies.

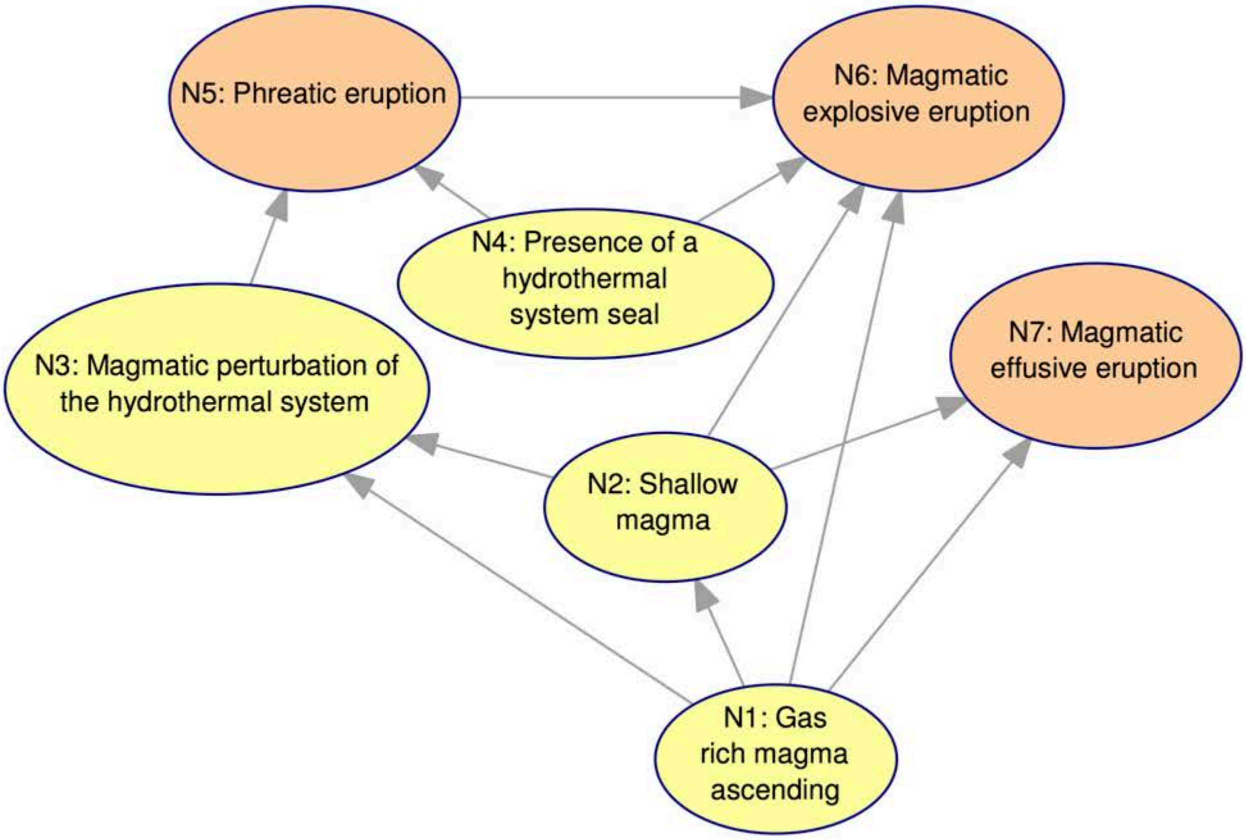

Figure 1: Extract from the BN for White Island magmatic eruption, describing the processes that cannot be observed directly (Yellow nodes) that can lead to eruption (orange nodes).

N1: Gas rich magma ascending

This node represents fresh gas-charged magma entering the system. Volatiles are driving the ascent of the magma into the upper part of the edifice. We assess the probability that gas-charged magma is ascending within any one-month period.

N2: Shallow magma

There is a general understanding that there has been shallow magma close to the surface at White Island for a while. Therefore we treat this node as a constant with only one state 'yes'. As a consequence, this node does not have direct influence on any subsequent nodes in the BN. Since the presence of "Shallow magma" is a significant component of the conceptual model of White Island, we keep this node within the BN model, even though it has no practical function in the BN.

N3: Magmatic perturbation of the hydrothermal system

Both "Gas rich magma ascending" and "Shallow magma" can lead to "Magmatic perturbation of the hydrothermal system", which again can lead to a "Phreatic eruption" (Node 5).

N4: Presence of a hydrothermal system seal

This node describes the partial or full sealing of the magma conduit that reduces gas emissions and allows gas to accumulate. Gas accumulation pressurises the conduit and can lead to more explosive phreatic eruptions. We assess the probability for a seal to be present within any one-month period.

Eruption nodes

We distinguish “N5: Phreatic eruption”, “N6: Magmatic explosive eruption”, and “N7: Magmatic effusive eruption”.

N5: Phreatic eruption

This node asks the question “What is the probability of a phreatic eruption within the next month that would impact beyond the rim of the 1976 - 2000 crater complex?” It is dependent on “Presence of a hydrothermal system seal” and “Magmatic perturbation of the hydrothermal system”.

N6: Magmatic explosive eruption

This node asks the question “What is the probability of a magmatic eruption within the next month that would impact beyond the rim of the 1976 - 2000 crater complex?” The node depends on “Gas rich magma ascending”, “Shallow magma”, and “Presence of a hydrothermal system seal”.

N7: Magmatic effusive eruption

This node asks the question “Is there a dome development or lava at the surface?” The node depends on “Gas rich magma ascending” and “Shallow magma.

Observations related to local seismicity

There are two continuously recording seismic broadband stations on White Island which have their records sent to GeoNet. Seismicity is probably the most reliable observable in the sense that it does not depend on weather or daylight to be recorded, and recordings are done continuously. The nearest station off the island is around 50 km away. Therefore we can only determine the depth of reasonably sized earthquakes and have no depth control on the more frequent small events. Thus we do not include any depth related nodes in the BN such as for example “hypocentres ascending”. There is currently no specific collection of seismic events for White Island.

We distinguish three types of earthquakes depending on their frequency content and we also have one type of tremor. For each of the earthquakes and for the tremor we have one node that describes a high rate currently observed, as well as a node that captures a recent high rate. The idea behind this it that the system has a memory and that recent activity can indicate that fluids or magma have shifted in the system. A further node “extended duration of earthquake swarm” (Node 14) gives an indication how long earthquake activity has been on-going. Here we do not distinguish the frequency content of the earthquake that contribute to the swarm because it may be difficult to measure the frequency content when more than one process is causing the earthquake occurrence as possible in the built-up to an eruption.

All of the earthquake nodes (N8-N14) have the same two parents: “Gas rich magma ascending” and “Magmatic perturbation of the hydrothermal system”. The tremor nodes (N15 and N16) in addition depend on “Shallow magma”. However, since “Shallow magma” is practically a constant, the conditions for all observations related to seismicity are basically the same.

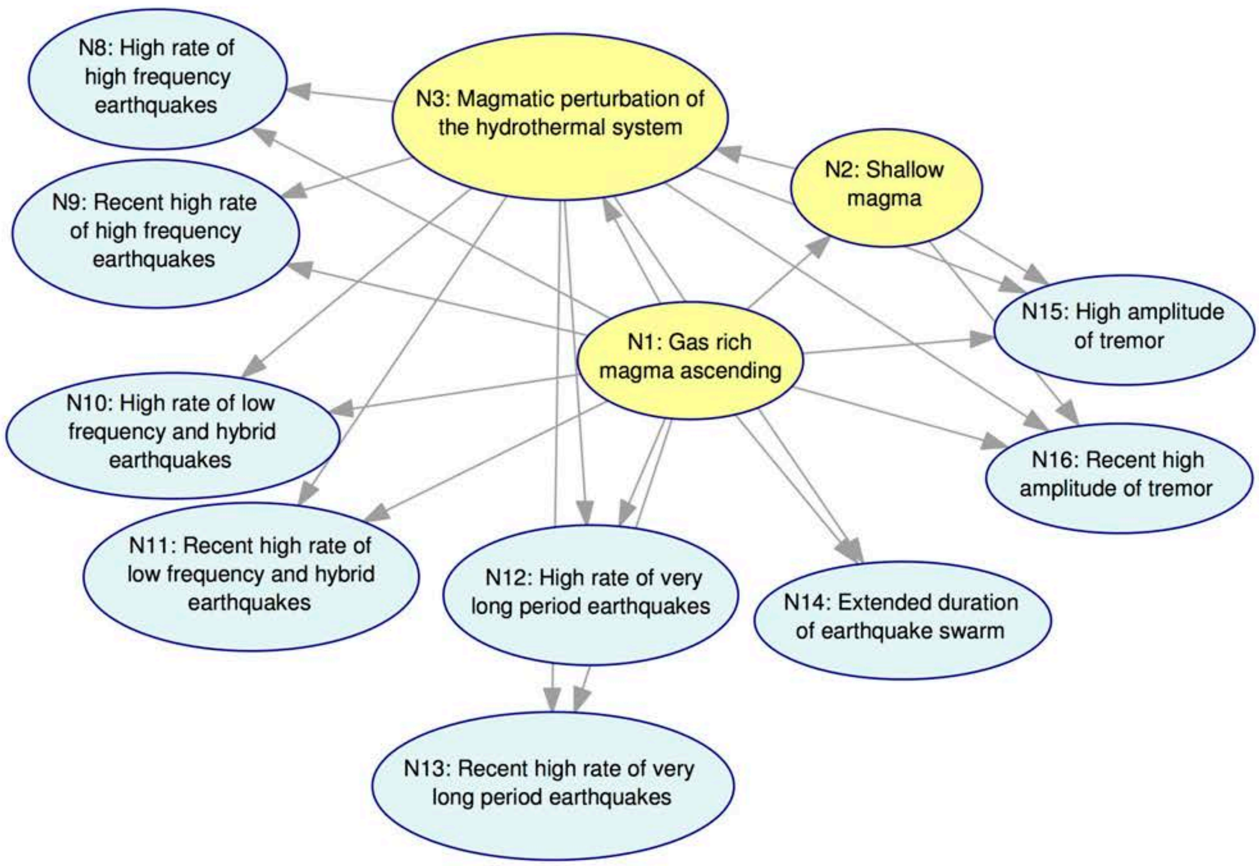

Figure 2: Extract from the BN for White Island, describing how the volcanic processes (yellow nodes) cause seismological observables (blue nodes). Note that we have removed the orange eruption nodes to keep the figure as simple as possible. We also removed "Presence of a hydrothermal system seal" because this node does not effect the observations related to local seismicity. A node "Seal rupture" would cause earthquake occurrence but we are currently not capturing the dynamic and shorter time scale processes.

N8: High rate of high frequency earthquakes

High frequency earthquakes are associated with rock breaking and thus an indication of stress. We ask for probability to observe a high rate of high frequency earthquakes conditional on "Gas rich magma ascending" and "Magmatic perturbation of the hydrothermal system".

N9: Recent high rate of high frequency earthquakes

This node captures whether a "High rate of high frequency earthquakes" has recently been observed. The node represents a memory of the system as described in the summary above.

N10: High rate of low frequency and hybrid earthquakes

Low frequency and hybrid earthquakes are possibly associated with fluid movement. We ask for the probability to observe a "High rate of low frequency and hybrid earthquakes" conditional on "Gas rich magma ascending" and "Magmatic perturbation of the hydrothermal system".

N11: Recent high rate of low frequency and hybrid earthquakes

This node captures whether a "High rate of low frequency and hybrid earthquakes" has been observed recently. The node represents a memory of the system as described in the summary above. We ask for the probability to observe "Recent high rate of low frequency and hybrid earthquakes" conditional on "Gas rich magma ascending" and "Magmatic perturbation of the hydrothermal system".

N12: High rate of very long period earthquakes

Very long period earthquakes are associated with significant fluid movement in subsurface. We ask for probability to observe “High rate of very long period earthquakes” conditional on “Gas rich magma ascending” and “Magmatic perturbation of the hydrothermal system”.

N13: Recent high rate of very long period earthquakes

This node captures whether a “High rate of very long period earthquakes” has been observed recently. The node represents a memory of the system as described in the summary above. We ask for probability to observe “Recent high rate of very long period earthquakes” conditional on “Gas rich magma ascending” and “Magmatic perturbation of the hydrothermal system”.

N14: Extended duration of earthquake swarm

The node captures any on-going seismicity. Here we do not distinguish between the frequency content of the earthquakes. We ask for probability to observe an “Extended duration of earthquake swarm”.

N15: High amplitude of tremor

Tremor is generally associated with unrest. High amplitude of tremor is linked to failure and eruption. We ask for the probability of “High amplitude of tremor” conditional on “Gas rich magma ascending”, “Shallow magma” and “Magmatic perturbation of the hydrothermal system”.

N16: Recent high amplitude of tremor

This node captures whether “High amplitude of tremor” has been observed recently. The node represents a memory of the system as described in the summary above. We ask for the probability of “Recent high amplitude of tremor” conditional on “Gas rich magma ascending”, “Shallow magma” and “Magmatic perturbation of the hydrothermal system”.

Observations related to surface processes

This part of the BN considers a range of observables including changes in the lake level (N18), lake or fumarole temperature (N20 and N21), local deformation (N19), large scale ground inflation as measured by GPS (N22), as well as high gas emissions through the lake (N17). Figure 3 shows how these observables are linked to the volcanic processes. Below we provide a brief description of each node.

N17: High gas emissions through lake (ebullition)

This node describes an obvious flow of gas through the lake. We ask for the probability of “High gas emission through lake” conditional on “Presence of a hydrothermal system seal” and “Magmatic perturbation of the hydrothermal system”.

N18: Lake level change independent of precipitation

This node describes either a rise of a fall in the lake level that does not seem to be related to precipitation. We ask for the probability of “Lake level change independent of precipitation” conditional on “Presence of a hydrothermal system seal” and “Magmatic perturbation of the hydrothermal system”.

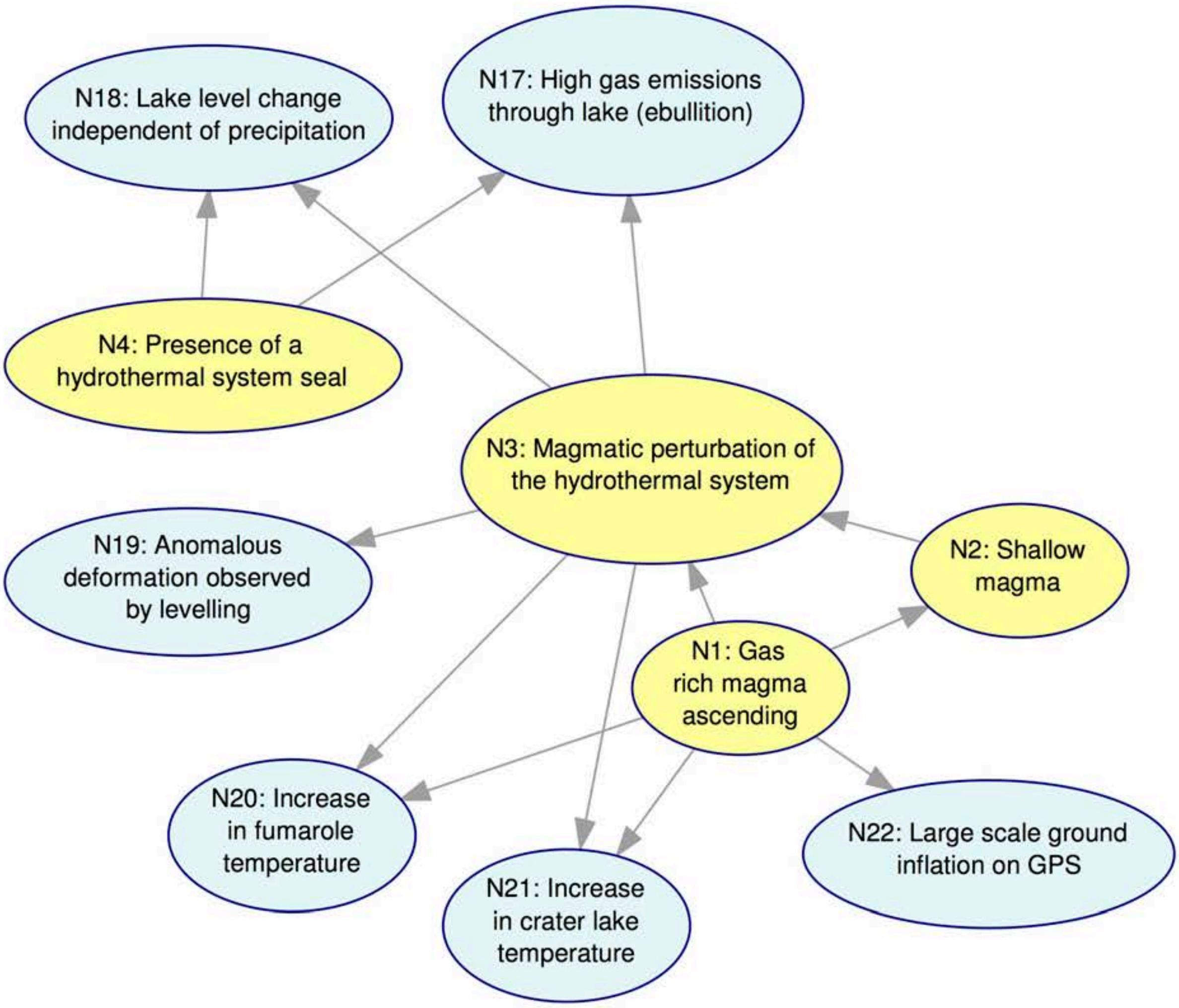

Figure 3: Extract from the BN for White Island, describing how the volcanic processes (yellow ovals) cause surface observations (blue ovals). Note that we have removed the orange eruption nodes to keep the figure as simple as possible.

N19: Anomalous deformation observed by levelling

This node describes a small area outside the crater complex moving up or down (Figure 4). We ask for the probability of "Anomalous deformation observed by levelling" conditional on "Magmatic perturbation of the hydrothermal system".

N20: Increase in fumarole temperature

This node represents one or more fumaroles showing a recent increase in temperature. We ask for the probability of "Increased in fumarole temperature" conditional on "Magmatic perturbation of the hydrothermal system" and "Gas rich magma ascending".

N21: Increase in lake temperature

This node represents the lake showing a recent increase in temperature. We ask for the probability of "Increase in lake temperature" conditional on "Magmatic perturbation of the hydrothermal system" and "Gas rich magma ascending".

N22 Large scale ground inflation on GPS

This node represents a large-scale elevation rise on White Island. We ask for the probability of "Large scale ground inflation on GPS" conditional on "Gas rich magma ascending".

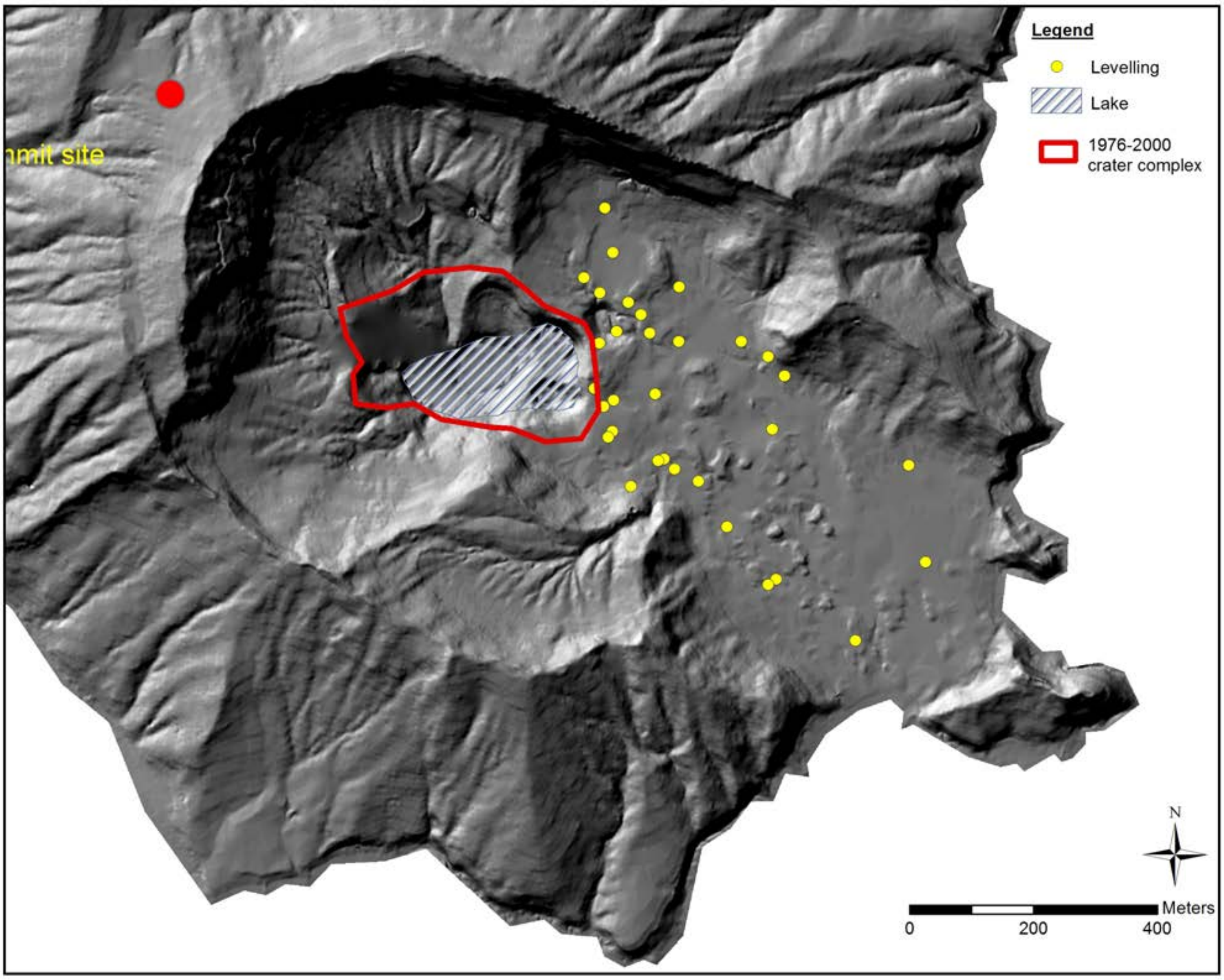

Figure 4: Map of White Island indicating levelling surveying locations, the 1976-200 crater complex and the current extent of the lake.

Observations related to changes in geochemistry

"Gas rich magma ascending" can lead to a number of possible changes in geochemistry, which we summarise in seven observable nodes. We distinguish between elevated gas flux of CO_2 and SO_2 in air and in fumaroles (N23-N25). These four nodes are dependent on all four volcanic processed nodes (N1-N4). Therefore we look at the same conditions when estimating the probability of those nodes. A further observable is "Elevated diffuse gas emission" and "Changes in the composition of fumaroles (N28) as well as springs and lakes (N29). Figure 5 shows how the observations linked to geochemistry (blue nodes) are dependent on the volcanic processes (yellow nodes).

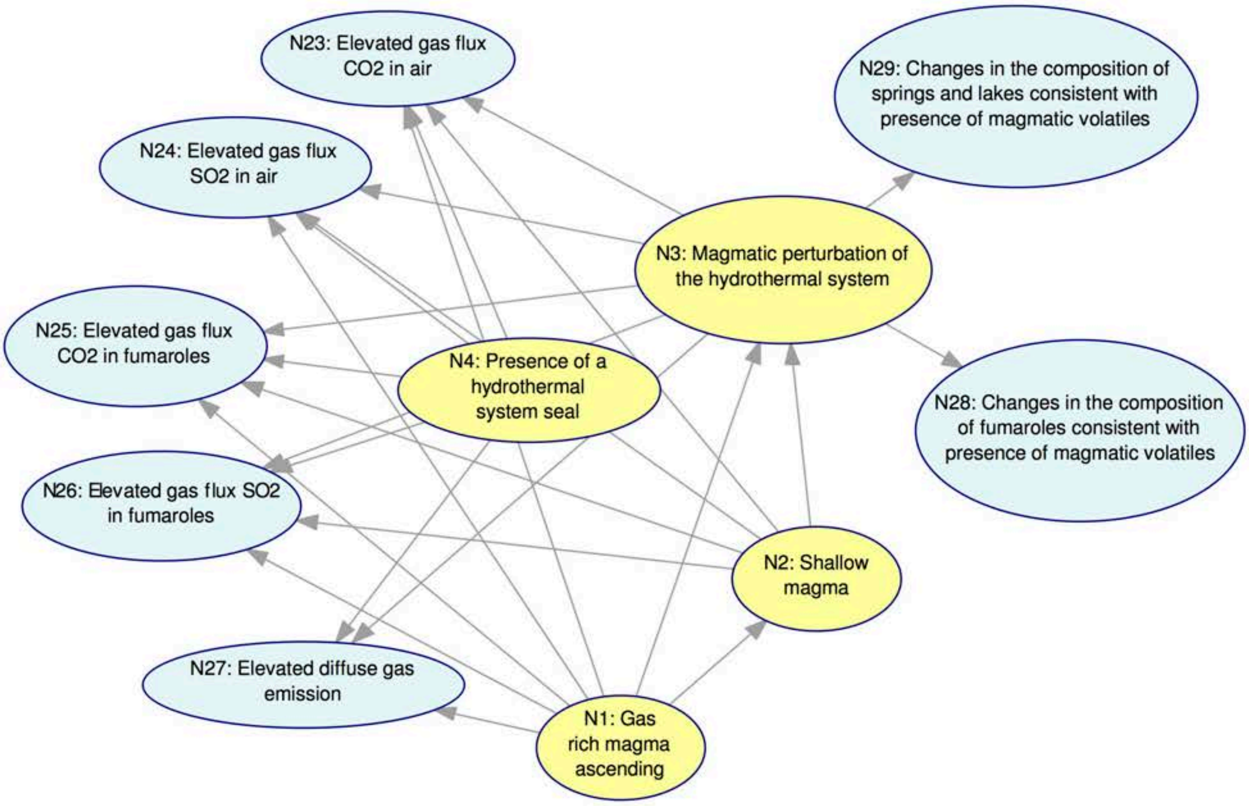

Figure 5: Extract from the BN for White Island, describing how the volcanic processes (yellow nodes) cause geochemical observations (blue nodes). Note that we have removed the orange eruption nodes to keep the figure as simple as possible.

N23: Elevated gas flux CO_2 in air

"Elevated gas flux of CO_2 in air" is an indication of "Gas rich magma ascending". CO_2 presence in the absence of SO_2 indicates deep de-gassing or shallow scrubbing of SO_2. We ask for the probability of "Elevated gas flux of CO_2 in air" conditional on "Gas rich magma ascending", "Shallow magma", "Magmatic perturbation of the hydrothermal system", and "Presence of a hydrothermal seal".

N24: Elevated gas flux SO_2 in air

This is an indication of "Gas rich magma ascending". We ask for the probability of "Elevated gas flux of SO_2 in air" conditional on "Gas rich magma ascending", "Shallow magma", "Magmatic perturbation of the hydrothermal system", and "Presence of a hydrothermal seal".

N25: Elevated gas flux CO_2 in fumaroles

Again, this is an indication of “Gas rich magma ascending”. We ask for the probability of “Elevated gas flux of CO_2 in fumaroles” conditional on “Gas rich magma ascending”, “Shallow magma”, “Magmatic perturbation of the hydrothermal system”, and “Presence of a hydrothermal seal”.

N26: Elevated gas flux SO_2 in fumaroles

Again, this is an indication of “Gas rich magma ascending”. We ask for the probability of “Elevated gas flux of CO_2 in fumaroles” conditional on “Gas rich magma ascending”, “Shallow magma”, “Magmatic perturbation of the hydrothermal system”, and “Presence of a hydrothermal seal”.

N27: Elevated diffuse (soil) gas emission

“Elevated diffuse (soil) gas emission” is also an indication of “Gas rich magma ascending”. We ask for the probability of “Elevated diffuse gas emission” conditional on “Gas rich magma ascending”, “Magmatic perturbation of the hydrothermal system”, and “Presence of a hydrothermal seal”.

N28: Changes in the composition of fumaroles consistent with the presence of magmatic volatiles

“Changes in the composition of fumaroles consistent with the presence of magmatic volatiles” is also an indication of “Gas rich magma ascending”. However, the change of the composition would be fed into the fumaroles through the hydrothermal system. Therefore we ask the probability of “Changes in the composition of fumaroles consistent with the presence of magmatic volatiles” conditional on “Magmatic perturbation of the hydrothermal system”. Only in case of very high temperature fumaroles of 800C and more would the hydrothermal system be circumvented.

N29: Changes in the composition of springs and lakes consistent with the presence of magmatic volatiles

“Changes in the composition of springs and lakes consistent with the presence of magmatic volatiles” is also an indication of “Gas rich magma ascending”. However, the change of the composition would be fed into the springs and lakes through the hydrothermal system. Therefore we ask the probability of “Changes in the composition of springs and lakes consistent with the presence of magmatic volatiles” conditional on “Magmatic perturbation of the hydrothermal system”.

Questionnaire for White Island Bayesian Network (BN)

Background and consent

The White Island BN is a first attempt to explore BN modelling as a decision support tool to probabilistically forecast volcanic eruptions in New Zealand. We have developed a BN model for White Island that simplifies the volcanic processes that lead to eruption to four nodes as explained in a separate 'workshop notes' document. The volcanic processes can lead to three types of eruptions and they also cause various observables. We have purposefully kept the BN model simple so that it hopefully satisfies different conceptual models that people may have.

Ethics
Completion of the survey implies consent. We therefore have asked you to sign a separate consent form. Your responses to this questionnaire will remain anonymous. When showing results of the survey, individual experts will be referred to as Expert 1, 2, etc. Every participant who is interested will get access to a BN with his or her individual results as well as the group's results. Data collected from this survey will initially be accessed by Annemarie Christophersen only. For later analysis data may be passed on to other researchers but without identification of the individual providing the data.

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher named below is responsible for the ethical conduct of this research.

If you have any questions about the survey, please contact Annemarie Christophersen, email a.christophersen@gns.cri.nz.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director (Research Ethics), telephone 06 356 9099 extn 86015, email humanethics@massey.ac.nz.

Questionnaire for White Island Bayesian Network (BN)

THE VOLCANIC PROCESSES LEADING TO ERUPTION

Name:

N1: Gas rich magma ascending

1. What is the probability of 'Gas rich magma is ascending' at White Island in any one-month period?

10th percentile

50th percentile

90th percentile

N3: Magmatic perturbation of the hydrothermal system

1. Given that **there is** 'Gas rich magma is ascending' and **there is** 'Shallow magma', what is the probability of 'Magmatic perturbation of the hydrothermal system' within a one-month period?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** 'Gas rich magma is ascending' and **there is** 'Shallow magma', what is the probability of 'Magmatic perturbation of the hydrothermal system' within a one-month period?

10th percentile

50th percentile

90th percentile

N4: Presence of a hydrothermal system seal

What is the probability of 'Presence of a hydrothermal system seal' at White Island in any one-month period?

10th percentile

50th percentile

90th percentile

N5: Phreatic eruption

1. Given that there **is** 'Magmatic perturbation of hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability to have 'Phreatic eruption' within the next month?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Magmatic perturbation of hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability to have 'Phreatic eruption' within the next month?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Magmatic perturbation of hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability to have 'Phreatic eruption' within the next month?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Magmatic perturbation of hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability to have 'Phreatic eruption' within the next month?

10th percentile

50th percentile

90th percentile

N6: Magmatic explosive eruption

1. Given that there **is** 'Gas rich magma ascending', there is 'Shallow magma', there is 'Presence of hydrothermal system seal', and 'Phreatic eruption' **occurred** within the last month, what is the probability of 'Magmatic explosive eruption' in the next month?

10th percentile

50th percentile

90th percentile

2. Given that there **is** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **did not** occur within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

3. Given that there **is** ‘Gas rich magma ascending’, there is ‘Shallow magma,’ there **is no** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **occurred** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

4. Given that there **is** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is no** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **did not occur** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

5. Given that there **is no** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **occurred** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **did not occur** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is no** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **occurred** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** ‘Gas rich magma ascending’, there is ‘Shallow magma’, there **is no** ‘Presence of hydrothermal system seal’, and ‘Phreatic eruption’ **did not occur** within the last month, what is the probability of ‘Magmatic explosive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

N7: Magmatic effusive eruption

1. Given that there **is** ‘Gas rich magma ascending’ and there **is** ‘Shallow magma’, what is the probability of ‘Magmatic effusive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** ‘Gas rich magma ascending’ and there **is** ‘Shallow magma’, what is the probability of ‘Magmatic effusive eruption’ in the next month?

10th percentile

50th percentile

90th percentile

Please provide any comments that you may have about the BN section ‘The volcanic processes leading to eruption’.

OBSERVATIONS RELATED TO LOCAL SEISMICITY

N8: High rate of high frequency earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'high rate' of high frequency earthquakes?

N9: Recent high rate of high frequency earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of high frequency earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'recent' high rate of high frequency earthquakes?

N10: High rate of low frequency and hybrid earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of low frequency and hybrid earthquakes?'

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'high rate' of low frequency and hybrid earthquakes?

N11: Recent high rate of rate of low frequency and hybrid earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of hydrothermal system', what is the probability of 'Recent high rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of hydrothermal system', what is the probability of 'Recent high rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is a** 'Magmatic perturbation of hydrothermal system', what is the probability of 'Recent high rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of hydrothermal system', what is the probability of 'Recent high rate of low frequency and hybrid earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'recent' high rate of low frequency and hybrid earthquakes?

N12: High rate of very long period earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of very long period earthquake'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'High rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'high rate' of very long period earthquakes?

N13: Recent high rate of very long period earthquakes

1. Given that there **is** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of very long period earthquake'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of a 'Recent high rate of very long period earthquakes'?

10th percentile

50th percentile

90th percentile

How do you define 'recent' high rate of very long period earthquakes?

N14: Extended duration of earthquake swarm

1. Given that there **is** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of an 'Extended duration of earthquake swarm'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of an 'Extended duration of earthquake swarm'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of an 'Extended duration of earthquake swarm'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of an 'Extended duration of earthquake swarm'?

10th percentile

50th percentile

90th percentile

How do you define 'extended duration' of earthquake swarm?

N15: High amplitude of tremor

1. Given that there **is** 'Gas rich magma ascending', there is 'Shallow magma', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High amplitude of tremor'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', and there is no 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High amplitude of tremor'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', and there is 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High amplitude of tremor'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', there is 'Shallow magma', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'High amplitude of tremor'?

10th percentile

50th percentile

90th percentile

How do you define 'high amplitude' of tremor?

N16: Recent high amplitude of tremor

1. Given that there **is** 'Gas rich magma ascending', there is 'Shallow magma', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Recent high amplitude of tremor'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', and there is no 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Recent high amplitude of tremor'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending', there is 'Shallow magma', and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Recent high amplitude of tremor'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending', there is 'Shallow magma', and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Recent high amplitude of tremor'?

10th percentile

50th percentile

90th percentile

How do you define 'recent' high amplitude of tremor?

Please provide any comments that you may have about the BN section 'Observations related to local seismicity'.

Questionnaire for White Island Bayesian Network (BN)

OBSERVATIONS RELATED TO SURFACE PROCESSES

N17: High gas emissions through lake (ebullition)

1. Given that there **is** 'Magmatic perturbation of the hydrothermal system' and that there**is** 'Presence of a hydrothermal system seal', what is the probability of 'High gas emissions through lake (ebullition)'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Magmatic perturbation of the hydrothermal system' and that there**is no** 'Presence of a hydrothermal system seal', what is the probability of 'High gas emissions through lake (ebullition)'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Magmatic perturbation of the hydrothermal system' and that there**is** 'Presence of a hydrothermal system seal', what is the probability of 'High gas emissions through lake (ebullition)'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Magmatic perturbation of the hydrothermal system' and that there**is no** 'Presence of a hydrothermal system seal', what is the probability of 'High gas emissions through lake (ebullition)'?

10th percentile

50th percentile

90th percentile

N18: Lake level change independent of precipitation

1. Given that there **is** 'Magmatic perturbation of the hydrothermal system' and that there**is a** 'Presence of a hydrothermal system seal', what is the probability of 'Lake level change independent of precipitation'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Magmatic perturbation of the hydrothermal system' and that there**is no** 'Presence of a hydrothermal system seal', what is the probability of 'Lake level change independent of precipitation'?

10th percentile

50th percentile

90th percentile

3. Given that there is no 'Magmatic perturbation of the hydrothermal system' and that there is 'Presence of a hydrothermal system seal', what is the probability of 'Lake level change independent of precipitation'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Magmatic perturbation of the hydrothermal system' and that there**is no** 'Presence of a hydrothermal system seal', what is the probability of 'Lake level change independent of precipitation'?

10th percentile

50th percentile

90th percentile

N19: Anomalous deformation observed by levelling

1. Given that there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Anomalous deformation observed by levelling'?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Anomalous deformation observed by levelling'?

10th percentile

50th percentile

90th percentile

N20: Increase in fumarole temperature

1. Given that there **is** 'Gas rich magma ascending' and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in fumarole temperature'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending' and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in fumarole temperature'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending' and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in fumarole temperature'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending' and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in fumarole temperature'?

10th percentile

50th percentile

90th percentile

How do you define 'increase' in fumarole temperature?

N21: Increase in crater lake temperature

1. Given that there **is** 'Gas rich magma ascending' and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in crater lake temperature'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending' and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in crater lake temperature'?

10th percentile

50th percentile

90th percentile

3. Given that there **is no** 'Gas rich magma ascending' and there **is** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in crater lake temperature'?

10th percentile

50th percentile

90th percentile

4. Given that there **is no** 'Gas rich magma ascending' and there **is no** 'Magmatic perturbation of the hydrothermal system', what is the probability of 'Increase in crater lake temperature'?

10th percentile

50th percentile

90th percentile

How do you define 'increase' in crater lake temperature?

N22: Large scale ground inflation on GPS

1. Given that there **is** 'Gas rich magma ascending', what is the probability of 'Large scale ground inflation on GPS'?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** ‘Gas rich magma ascending’, what is the probability of ‘Large scale ground inflation on GPS’?

10th percentile

50th percentile

90th percentile

Please provide any comments that you may have about the BN section ‘Observations related to surface processes’.

Questionnaire for White Island Bayesian Network (BN)

OBSERVATIONS RELATED TO CHANGES IN GEOCHEMISTRY

N23: Elevated gas flux CO_2 in air

1. Given that there **is** ‘Gas rich magma ascending', there is ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there is ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile	
50th percentile	
90th percentile	

2. Given that there **is** ‘Gas rich magma ascending', there is ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile	
50th percentile	
90th percentile	

3. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile	
50th percentile	
90th percentile	

4. Given that there **is** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there is no ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile	
50th percentile	
90th percentile	

5. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in air’?

10th percentile

50th percentile

90th percentile

How do you define “elevated” gas flux CO_2 in air?

Node 24: Elevated gas flux SO_2 in air

1. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in air'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in air'?

10th percentile

50th percentile

90th percentile

3. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in air'?

10th percentile

50th percentile

90th percentile

4. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in air'?

10th percentile

50th percentile

90th percentile

5. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in air'?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux SO_2 in air’?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux SO_2 in air’?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux SO_2 in air’?

10th percentile

50th percentile

90th percentile

How do you define “elevated” gas flux SO_2 in air?

N25: Elevated gas flux CO_2 in fumaroles

1. Given that there **is** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

2. Given that there **is** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

3. Given that there **is** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

4. Given that there **is** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

5. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Shallow magma’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated gas flux CO_2 in fumaroles’?

10th percentile

50th percentile

90th percentile

How do you define ‘elevated’ gas flux CO_2 in fumaroles?

26: Elevated gas flux SO_2 in fumaroles

1. Given that there **is** 'Gas rich magma ascending', there is 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

2. Given that there **is** 'Gas rich magma ascending', there is 'Shallow magma', there is 'Magmatic perturbation of the hydrothermal system' and there is no 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

3. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

4. Given that there **is** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

5. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is** 'Magmatic perturbation of the hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** 'Gas rich magma ascending', there **is** 'Shallow magma', there **is no** 'Magmatic perturbation of the hydrothermal system' and there **is no** 'Presence of a hydrothermal system seal', what is the probability of 'Elevated gas flux SO_2 in fumaroles'?

10th percentile

50th percentile

90th percentile

How do you define “elevated” gas flux SO_2 in fumaroles?

N27: Elevated diffuse gas emission

1. Given that there **is** ‘Gas rich magma ascending‘, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

2. Given that there **is** ‘Gas rich magma ascending‘, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

3. Given that there **is** ‘Gas rich magma ascending‘, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

4. Given that there **is** ‘Gas rich magma ascending‘, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

5. Given that there **is no** ‘Gas rich magma ascending', there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

6. Given that there **is no** ‘Gas rich magma ascending’, there **is** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

7. Given that there **is no** ‘Gas rich magma ascending’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

8. Given that there **is no** ‘Gas rich magma ascending’, there **is no** ‘Magmatic perturbation of the hydrothermal system’ and there **is no** ‘Presence of a hydrothermal system seal’, what is the probability of ‘Elevated diffuse gas emission’?

10th percentile

50th percentile

90th percentile

How do you define ‘elevated’ diffuse gas emission?

N28: Changes in the composition of fumaroles consistent with presence of magmatic volatiles

1. Given that there **is** ‘Magmatic perturbation of the hydrothermal system’, what is the probability of ‘Changes in the composition of fumaroles consistent with presence of magmatic volatiles’?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** ‘Magmatic perturbation of the hydrothermal system’, what is the probability of ‘Changes in the composition of fumaroles consistent with presence of magmatic volatiles’?

10th percentile

50th percentile

90th percentile

N29: Changes in the composition of springs and lakes consistent with presence of magmatic volatiles

1. Given that there **is** ‘Magmatic perturbation of the hydrothermal system’, what is the probability of ‘Changes in the composition of springs and lakes consistent with presence of magmatic volatiles’?

10th percentile

50th percentile

90th percentile

2. Given that there **is no** ‘Magmatic perturbation of the hydrothermal system’, what is the probability of ‘Changes in the composition of springs and lakes consistent with presence of magmatic volatiles’?

10th percentile

50th percentile

90th percentile

Please provide any comments that you may have about the BN section ‘Observations related to changes in geochemistry’.

White Island BN workshop: Feedback Form

Thank you for taking part in this workshop. Please fill in this form as we wrap up the workshop.

1. Name: 2. How would you describe your expertise/discipline?	
3. During the workshop we discussed to evaluate the results according to experts' level of confidence in their own knowledge for the different areas of the BN. 1. The volcanic processes leading to eruption 2. Observations related to seismicity 3. Geophysical and surface observations 4. Observations related to geochemistry.	Please rate the following areas of the BN in order of your confidence in your knowledge from 1 (not very confident) to 10 (very confident): _____ _____ _____ _____
4. Are you comfortable with the BN data being presented grouped according to experts' confidence level? Please circle: Yes No Not sure Any comments?	

Elicitation of the New Node: Fresh glass observed

1. Given that there is “Gas rich magma is ascending” and there is “Shallow magma”, what is the probability of “Fresh glass observed” within a one-month period?

   10th   50th   90th

2. Given that there **is no** “Gas rich magma is ascending” and there is “Shallow magma”, what is the probability of “Fresh glass observed” within a one-month period?

10th   50th   90th

What is your understanding of ‘hydrothermal system seal’?

5. The following questions are about your interest in the analysis of the data and how you would like to be kept informed.
5.a) There were 115 different conditions that everyone assessed. Annemarie is likely to start just looking at plots to see how the answers vary between experts. Are you interested in those plots?

Please circle: Yes No Not sure

Other comments:

5.b)Would you like to receive your data in a Bayesian Network file?

Please circle: Yes No Not sure

5.c) Would you like to get an introduction into the Genie software to work with the BN data?

Please circle: Yes No Not sure

5.d) If yes to the above, please say how this could best be delivered to you, e.g. written instruction, video clip demo, group training, etc?

Do you have any other comments/suggestions about data analysis and use of data?

6. This part of the questionnaire is about your general impression of the White Island BN

6.a) What’s you view on the nodes ? Have we captured the main processes? Is there anything missing? Are some nodes not as useful as others?

6.b) What are your thoughts on the definition of the states? Do you have suggestions for any improvements?

6.c) Without having seen any results yet what is your impression of its usefulness? How do you see the BN being used?

7. This part of the questionnaire is about future BN modelling work. Do you see yourself being involved in any further BN modelling activity? Please circle:

7.a) Interested in future model development for volcanic monitoring and eruption forecasting	Yes	No	Not sure
7.b) Interested in participating in future expert elicitation workshops	Yes	No	Not sure
7.c) Interested in using BN modelling in my own area of research	Yes	No	Not sure

Please provide any comments that you may have, also on where you see priority of future work, e.g. further development of methods (particularly continuous BNs), sensitivity testing; model testing on eruption data; application to other volcanoes

8. During the workshop we followed procedure of Structured Expert Elicitation in that we (1) used calibration questions to introduce the concept of estimating uncertainty, and (2) answered questions individually following a general discussion about the subject matter. However, this time we do not use calibration questions to weight experts' contributions. What are you thoughts on

8.a) the procedures?

8.b) using calibration questions for weighting in the future?

Feedback on the workshop (e.g., length, programme, format, explanations, BN questionnaire)

What worked well?
What didn't work so well and how could it be improved?

Do you have any other comments?

Thank you! Please email form to: A.Christophersen@gns.cri.nz