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Aso volcano: estimating the probabilistic likelihood of a future Aso4-scale eruption from stochastic uncertainty analysis of volcanological evidence using importance sampling

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Abstract

The Aso4 explosive eruption on Kyushu, Japan, 89,500 years ago was one of the biggest global eruptions in the last one hundred millennia, with a magnitude of approximately M8. Its effects were widespread throughout Japan; a similar scale event now would have huge societal impact. Today, 6.5 million persons live within 100 km of Aso. The key question for disaster preparedness and mitigation is: what is the likelihood of another M8 eruption from Aso-san? We estimate the probability of such an event within the next 100 years so that the scenario and its threats can be compared to other potential natural disasters. To evaluate this probability, we performed a comprehensive stochastic uncertainty analysis using advanced computational Bayes Net (BN) software. Our BN eruption process model is informed by multiple strands of evidence from volcanology, petrology, geochemistry and geophysics, together with estimates of epistemic (knowledge) uncertainty, adduced from reviews of published data, modelling and from expert judgement elicitation. Several lines of scientific evidence characterise the likely structure, magma composition and eruptibility state of the present-day volcano, which has had numerous smaller eruptions since Aso4. An initial analysis indicated that another Aso4-scale event has an extremely low likelihood, being less than 1 - in - 10 million in the next 100 years (i.e. $< 10^{-7}$ probability). To further constrain this probability, we implemented probabilistic 'importance sampling' in our BN to allow even smaller probabilities to be enumerated. We find that the chance of an Aso4-scale eruption (characterised by mean volume 500 km^3 DRE, 90% credible interval [370 .. 685] km^3 DRE) is less than 1 – in – 1 billion in the next 100 years (i.e. $<10^{-9}$ probability). We doubt that this conclusion, based on current understanding and evidence, could be different by more than an order of magnitude.

Keywords: Volcanic Eruption, Volcanic Hazards, Stochastic Uncertainty Analysis, Importance Sampling, Bayes Net (BN)

1. Introduction

We describe a Bayes Net (BN) model designed to estimate the probability that a future explosive eruption of Aso volcano (Figure 1), occurring within the next 100 years, could produce a total volume of erupted magmatic products that could equal or exceed the volume erupted in the Aso4 event, 89.5 kyr BP. Almost all the volcanological, geological and geophysical aspects of the problem involve substantial scientific uncertainties; these are represented in our BN model to the extent they are informed by observational data, theory or expert judgment.

In this study, we conducted an exhaustive literature collection in 2019-2020, built an initial BN model, and completed the BN model by considering the most recent and important literature published by March 2021. Published research is the main evidential basis for our BN model, supplemented by a series of separate, commissioned specialist studies.

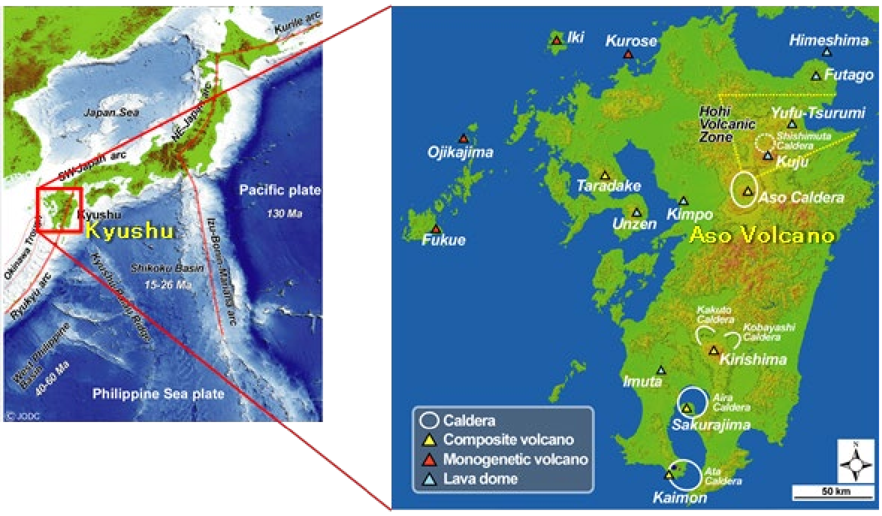

Figure 1: Location of Aso Volcano in Kyushu, Japan (from Chapman et al., 2009)

We discuss the way these various appraisals of the Aso4 eruption are combined with a fundamental advance in stochastic uncertainty modelling to refine the basis for re-calculating the probability of a near future eruption on the scale of Aso4. In this study, we argue – on compelling geological, geophysical and volcanological grounds – that the likelihood of such an eruption within the next 100 years is extraordinarily low, so low that it could not be calculated previously using conventional methods for estimating event potential occurrence probability.

2. Approach

In the light of our new work and with the publication of an important paper discussing Aso4 eruption deposit volumes (Takarada and Hoshizumi, 2020), a key part of this study has been to re-determine the magnitude of the Aso4 eruption and, critically, to estimate the uncertainty associated with that magnitude estimate. While this partly relied on information in the literature, we also took advantage of significant improvements in numerical analysis techniques applied to field data. Our approach involved a detailed review and comparative study of previous Aso4 erupted volume estimates and methods, and the application of an advanced statistical modelling technique for integrating contoured isopach (thickness) data to estimate total deposit volumes. The key point here is that the Aso4 eruption volume/magnitude – with formally assessed uncertainty – is the critical scaling parameter against which we test for the probability that a near-future explosive eruption of Aso could equal (or exceed) the Aso4 volume.

Recently published investigations on the composition and origins of Aso4 magma (Ushioda et al., 2020) and post-Aso4 magma (Kawaguchi et al., 2021) help constrain our understanding of the petrogenesis of Aso volcano and provide an enhanced framework to interpret evolutionary trends of post-Aso4 silicic and mafic magmatism. This, and other published petrological information, is used to develop a conceptual model of the current and near-future Aso volcano magma system. Thus, our new analyses of related geophysical data, together with improved petrological insights, are synthesized through expert elicitation to inform parameter revisions for nodes in our BN model that represent reservoir sizes, compositions, and eruptible volumes.

Benefit is also taken from new numerical advances in performing importance sampling analysis (Rubin, 1987), within the BN framework, enabling stochastic modelling calculations to be undertaken which relate to events and situations with hitherto unquantifiable extremely low probabilities of occurrence; coupled with these stochastic modelling developments, advantage is taken of the increased capacity to process massive spreadsheet datasets afforded by the Data Model and Power Query capabilities in the current version of Excel software (Microsoft 365 Apps for Enterprise version 2104).

3. Aso Bayes Net design

The essential theme of the Aso BN is a magma-volume accounting model with two main elements: the total volume of magma that was erupted 89.5 kyr BP, and the estimated total volume of eruptible magma that may currently reside within the volcano (or become present within the next 100 years). The lines of evidence informing these aspects are many, varied, and all entail uncertain parameters; thus, these are treated as random variables (RV) in a BN framework. Magma composition is another critical element: the Aso3-4 large magnitude explosive eruptions were silicic in composition. There is no evidence from the geological records that silicic volcanoes are capable of large explosive eruptions of the kind that create large calderas, such as that formed by Aso4. Thus, our Aso BN includes an assessment of the probability that the present stored magma is mafic or silicic.

The numerical analysis uses stochastic sampling of the multiple RV uncertainty distributions (and other variables and factors which feed into them) to ascertain the probability that the available eruptible magma volume could equal or exceed the estimated Aso4 erupted volume. This is implemented using the UNINET software package, developed originally by TU Delft in The Netherlands (now maintained by LightTwist Software https://lighttwist-software.com/). UNINET is an advanced analytical graphical program for high-dimension stochastic uncertainty modelling, multivariate data mining and machine learning, using the Bayes Net paradigm, probability vines and dependence trees.

The framework of our complete Aso BN comprises three parts:

[a] a network of the nodes to model contributory lines of evidence for numerical estimation of the composite total volume of the Aso4 deposits, shown schematically in Figure 2;

[b] a second network for the nodes that represent lines of evidence informing the numerical estimation of the total volumes of eruptible magma available in reservoirs in the present-day volcano, which includes the next 100 years (BN model not shown here);

[c] a sub-net of nodes which contain numerical information about partial statistical cumulative distribution functions (CDFs) for total Aso4 volume and for eruptible reservoir magma volume, used for importance sampling and for estimating the probability of an Aso4-scale eruption in the next 100 years, described below. These partial CDFs are drawn from the range of sample volumes that jointly overlap in both the Aso4 total volume samples probability density function (PDF - obtained from enumeration of the nodes and branches comprising Figure 2) and in the total eruptible volume samples PDFs from the second part BN (not shown).

Here, we present only the first part of our BN: i.e. the framework for estimating the total volume of the Aso4 eruption from deposit data – see Figure2.

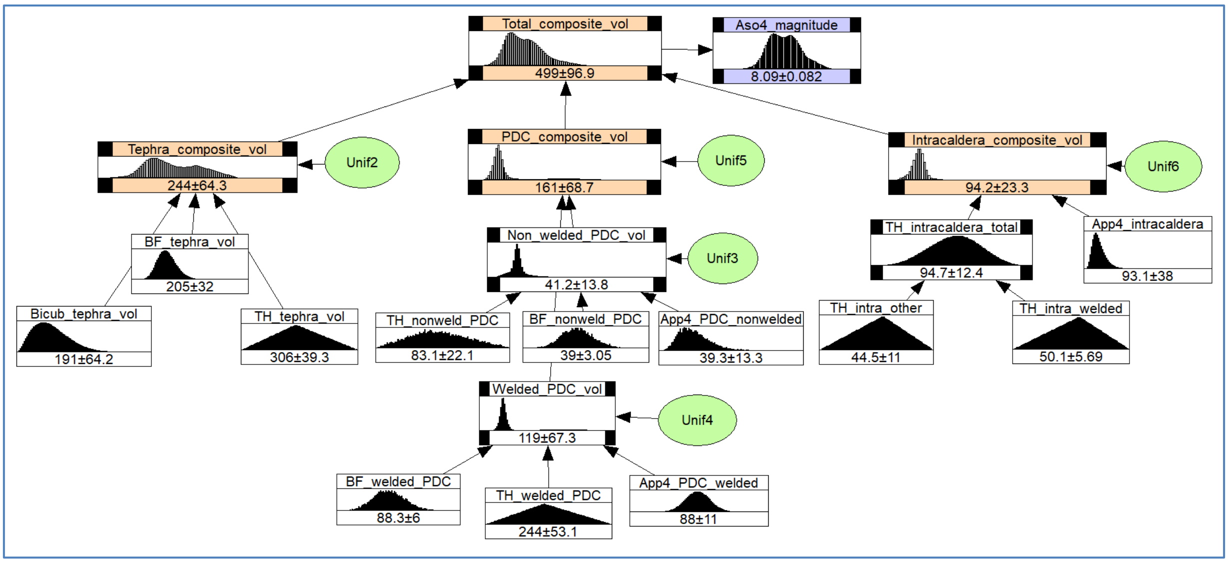

Figure 2: Aso4 deposits volume synthesis: BN model nodes and resulting PDFs in UNINET graphical form. Numbers in each panel indicate mean value and standard deviation; full PDF statistics can be extracted for further analysis. Deposit volumes are expressed as Dense Rock Equivalent (DRE), for direct comparison with magma volumes.

*Key: App4_* relates to geophysical data or values from a study appendix report; *BF_* basis function values (determined in a separate study); *Bicub_* indicates values obtained from bicubic spline fitting modelling (previous report); *Comb* means "combination"; *Nonweld* is for non-welded PDC / ignimbrite data; *PDC* "pyroclastic density current"; *TH_* denotes data or values from Takarada and Hoshizumi (2020); *Unif_* is uniform distribution on interval [0..1]; *_vol* or *Vol_* denote "volume".

In Figure 2, nodes representing input data, variables or parameter distributions are shown as plain rectangles (or ellipses); calculational (functional) nodes are shown as with black corner/ blocks. The latter contain equations or dependence conditions for operating on variable samples from data nodes to which they are linked by arrows (‘arcs’ in BN terminology). Top level nodes, representing the key outputs from the BN networks have coloured borders for identification purposes. Green nodes, labelled “*Unif*” etc., are simple uniform PDFs on the interval [0 .. 1], sampled randomly to activate relative weights where needed for alternative data options selection in linked calculational nodes.

For input nodes derived for the BN, our various independent volume estimates and associated uncertainties are expressed as Normal distributions with means and standard deviations to match analysis results. For parameters which can take only positive real values (e.g. physical volumes), we adopt lognormal PDFs to avoid having negative value samples in such distributions.

For Takarada & Hoshizumi (2020) parameter spreads (i.e. Figure 2 nodes labelled: *TH_xxxx*), these are represented by triangular distributions to accord with the way those authors reported their findings. In our model, the triangular distributions are extended below and above the TH minimum and maximum values allowing the reported endpoint values to be actively sampled as actual values. In effect, this is tantamount to ascribing arbitrary – but realistic – uncertainties to minimum and maximum values for stochastic sampling purposes. To implement this intrinsic range adjustment to their variables, the distributions are here extended beyond Takarada and Hoshizumi’s bounding values by 10% below the relevant minima to 10% greater than their maxima. Simple tests suggest these extension values are not critical and appear reasonable for the present application and circumstances.

Hints of bimodality in the top-level nodes arise from combining different contributing sub-type deposit PDFs (second row nodes); they are not considered to imply any substantive physical meaning.

The results of computing the various contributory Aso4 volumes can be read off the BN chart Figure 2; the key composite (summed/combination) results are summarised on Table 1:

Table 1 Aso4 deposit volumes: summary means and standard deviations

	Mean	Stdev	
Vol_tephra	209	60	km^3 DRE
Vol_PDC	161	69	km^3 DRE
Vol_intracaldera	94	23	km^3 DRE
Aso4_total_vol	499	97	km^3 DRE

The absolute smallest sample volume is about 212 km^3 DRE, which is less than Takarada and Hoshizumi (2020) minimum estimate of 465 km^3 DRE. The greatest BN sample volume, 1202 km^3 DRE, also exceeds Takarada and Hoshizumi (2020) maximum bound of 962 km^3 DRE.

When converted to equivalent eruption magnitudes, the BN determined DRE volumes equate to:

Mean magnitude M8.1 ± 0.08 magnitude units

M7.7 (minimum); M8.0 (5th %ile); M8.1 (median); M8.2 (95th %ile); M8.5 (maximum). (1)

The LaMeve database (Crosweller et al, 2012) reports Aso4 eruption magnitude as M7.7; Takarada and Hoshizumi (2020) suggest M8.1 – 8.4. The magnitude uncertainty distribution from our study, enumerated by the BN analysis, spans these published magnitude values; our mean magnitude M8.1 accords with the lower of Takarada and Hoshizumi’s values.

This correspondence engenders confidence that our BN-derived PDF for the volume/magnitude of Aso4 is an appropriate basis for quantifying the probability of an eruption on this scale in the next 100 years, discussed in the next section.

4. Computational enumeration of Aso4-scale eruption exceedance probability

To estimate the probability of an Aso4-scale eruption in the next 100 years, we introduce a novel ‘importance sampling’ technique into our BN analysis. Attempts to resolve a very low event probabilities (e.g. well below 10^{-6} probability) by ‘brute force’ Monte Carlo simulation requires upward of a billion samples and is simply not feasible with ordinary software. However, ‘importance sampling’ inference methods (e.g. Rubin, 1987) can be used to estimate posterior densities or expectations in state- or parameter estimation probabilistic models that are too hard to treat analytically, for example in Bayes nets.

In the present study, a separate sub-net is constructed that can selectively use just those fractional parts of parameter statistical distributions in the main BN model that are relevant to the uncertainty space of interest. That is, we analyse only those samples with large-scale potential eruption volumes, large enough to be close to or exceed corresponding 'low-end' stochastic samples from the estimated Aso4 volume distribution. Importance sampling is, thus, a numerically feasible replacement for an unattainable full-scale sampling approach.

Importance sampling inference is applied here, as follows. With the dual branched BN model, outlined in Section 3 above – i.e. comprising the Aso4 volume estimator in Figure 2 and the available eruptible volume estimator net (not shown) – the upper tail of the PDF for available eruptible volume just overlaps the lower tail of the PDF for node <*Total_composite_vol*> (i.e. the Aso4 eruption volume estimate, per Figure 2); the overlap covers the range 213 – 350 km^3 DRE. When the dual BNs are run jointly with 20 x 10^6 samples, just 73 samples are found in the overlap range for <*Total_eruptible_vol*>, while 23,138 samples are obtained for <*Total_composite_vol*>. The latter ≈23k samples represent only about 0.1% of the original 20 million samples!

UNINET's conditionalized sampling option is used to export those samples, drawn from each BN top-level node <*Total_eruptible_vol*> and <*Total_composite_vol*>, which fall inside the overlap range. These samples are processed with Excel to define cumulative density functions (CDF) to characterise the tail properties of the two variable distributions. The resulting CDFs are input back into the importance sampling sub-net of the BN, for the target exceedance probability calculations. This probability is determined by multiplying the importance samples' exceedance probability test distribution <*Eruptible_ge_Aso4*> jointly with the two sample size ratios; thus, the equation for enumerating the probability of an Aso4-scale eruption in 100 years is shown (2):

Pr[Eruptible_ge_Aso4 | importance sampling] * (73/Number_Samples) * (23138/Number_Samples) (2)

where Number_Samples from the main BN is 20 x 10^6.

One million iterations of the importance sampling BN sub-net are sufficient for calculating the required exceedance probability to an appropriate precision.

Without importance sampling, the main BN model – with maximum 20 million samples allowed by the software – fails to find a single instance where the potential future eruption volume exceeds the smallest volume quantified in the Aso4 eruption distribution. This demonstrates that the probability of an Aso4-scale eruption in the next 100 years is definitively lower than 5 x 10^{-8}, but fails to enumerate exactly how low it is.

Thus, to resolve this issue, recourse to the advanced and innovative importance sampling technique, just outlined, is indispensable. When the BN model top-level volume nodes overlap samples are jointly pooled in importance sampling mode, as just described, the mean probability of an Aso eruption in the next 100 years is enumerated about 5.6 x 10^{-10}. The associated standard deviation on this mean – derived from all the parameter uncertainties included in the BN – is: ±1.4 x 10^{-9}. Numerical uncertainty analysis indicates the corresponding 99% confidence level eruption probability is not greater than 4.2 x 10^{-9}.

These results are determined numerically from computations in our BN framework, which is based on all the geological, geophysical and volcanological evidence that contributes to model parameterisation.

For most purposes, and to avoid spurious precision, the probability values given here should be rounded to the nearest single significant digit, i.e. 6 x 10^{-10} (mean probability) and 4 x 10^{-9} (99% confidence).

5. Discussion and conclusions

To provide some context for our new assessment of the likelihood of an Aso4-scale eruption in the next 100 years, previous calculations with an earlier version of the Aso initial BN model using conventional numerical techniques, could show only that the probability of such an eruption was likely to be less than 1 x 10^{-7} (i.e. 1-in-10 million chance); in a following study, with some advances in stochastic modelling techniques, the Aso4-scale eruption probability in the next 100 years estimate was refined and evaluated at about 2 x 10^{-9}.

With the current BN model run in UNINET with importance sampling and relying on our re-appraised lines of volcanological evidence, **the mean probability of an Aso eruption in the next 100 years is enumerated at about 6 x 10^{-10}**. The standard deviation on this mean – derived from all the parameter uncertainties now included in our model – is: ±1.4 x 10^{-9}. This numerical uncertainty analysis indicates the corresponding 99% confidence level eruption probability is not greater than 4 x 10^{-9} in the next 100 years. It is noteworthy that this, our 99% confidence probability, is radically smaller than 3 ×

10^{-4} probability in 100 years, which would be a naive interpretation of the fact that there has been one Aso4-scale eruption over 300 kyr BP.

Assuming the latter, simplistic basis for inferring a mean century rate for Aso4-scale eruptions of Aso is invalidated by the geological evolution of the volcano, especially since the Aso4 event. Our conceptual model for the present Aso magma system is represented in the BN model by shallow, intermediate, and deep magma reservoirs, which are evaluated for ranges of eruptible volumes and compositions. With our latest revisions to BN node parameters, the minimum plausible value for the Aso4 total eruption volume is 212 km^3 DRE. In order for a present-day (i.e., including next 100 years) eruption to reach this lowest bound volume – without involving the deep magma reservoir – would require 86% evacuation of the maximum sample volume from the shallow magma reservoir (i.e. 95 km^3 DRE) and of the maximum sample volume from the intermediate magma reservoir volume (i.e. 150 km^3 DRE). Alternatively, 100% evacuation of the shallow reservoir maximum volume plus 78% of the intermediate reservoir maximum volume would achieve the required total volume. Both these scenarios, however, are dependent on the shallow and intermediate magma reservoirs being wholly silicic in composition – a very improbable scenario.

Clearly, if the 'target' volume for a future Aso4-scale eruption is greater than the sum of these two reservoir maxima, i.e. 95 + 150 = 245 km^3 DRE, then silicic magma from the deep reservoir must become involved in a prospective future eruption on the scale of Aso4. The critical assumption in this line of argument is that the shallow and intermediate reservoir volumes are both currently charged entirely with silicic magma to their (barely credible) maximum volumes. If either, or both, has substantially smaller capacity – and only low fractions of available reservoir volumes can be evacuated in eruption (as would be expected from volcanological considerations) – then a very substantial volume of deep reservoir silicic magma would need to be present, and eruptible, to plausibly match the scale of an event approaching our estimate of the mean volume of the Aso4 eruption.

From all petrological and geophysical considerations, however, the existence of such massive volumes of silicic magma at intermediate-to-lower crustal depths below Aso volcano, at the present time, is not deemed credible. Moreover, the prevailing compositions of the current shallow and intermediate magma systems are judged to be predominantly mafic, with only small likelihoods that the magmas which exist in these reservoirs are predominantly silicic.

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