研究報告

Probabilistic Approaches for Predicting the Long-Term Spatial and Temporal Characteristics of Monogenetic Volcanoes; Application to Two Monogenetic Volcano Fields in Japan.

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火山活動の長期予測における確率論的アプローチ；日本列島の２つの単成火山群を例として

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地質環境の長期安定性を評価するためには，地殻変動や火山活動等といった将来の自然現象を予測するための技術開発が不可欠である。我が国における火山活動の予測に関する研究は，主に防災対策の観点から，既存の活火山において想定される噴火様式や被害の程度等の評価を中心に進められてきたが，新たな火山の発生の可能性等といった数万年オーダを対象とした予測に関する研究はほとんど行われていない。本研究では，空間統計学に基づく確率モデル（１：空間モデル，２：時空間モデル，３：地殻構造，火道配列等を考慮した修正時空間モデル）を用いて東伊豆単成火山群，山陰地方東部の神鍋・扇ノ山単成火山群を例として長期的な火山活動の予測を試みた。

Volcanic hazard analyses are required for the assessment of the long-term stability of the geological environment. In Japan, a lot of research has been focused on the construction of volcanic hazard maps in the event of a volcanic eruption for natural disaster management, but not on the probability of new volcanic edifices forming within or nearby volcanic fields for long-term forecasting. In this paper, the development of the probabilistic approach is described and the preliminary results of probabilistic case studies on the Higashi-Izu (59 vents) and the Kannabe-Oginosen (38 vents) Monogenetic Volcano Groups in Japan are illustrated using: (1) a spatial (S) model; (2) a spatio-temporal (S-T) model; and (3) a modified spatio-temporal (M-S-T) model that better reflects shallow crustal features and/or vent alignments.

キーワード

火山活動，長期予測，点過程，確率解析，空間モデル，時空間モデル，修正時空間モデル，東伊豆単成火山群，神鍋・扇ノ山単成火山群，火道

Volcanism, Long-Term Forecasting, Point Process, Probabilistic Analysis, Spatial Model, Spatio-Temporal Model, Modified Spatio-Temporal Model, Higashi-Izu Monogenetic Volcano Group, Kannabe-Oginosen Monogenetic Volcano Group, Vent

1. Introduction

Volcanism is a low-frequency, high-consequence geologic hazard. As a result, volcanic hazard analyses are required for the assessment of the long-term stability of the geological environment[1), 2)]. Before any volcanic hazard analysis can be undertaken, it is first necessary and logical to quantify objectively, the probability of a volcanic

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eruption occurring. Japan is an active island arc consisting of approximately 350 Quaternary volcanoes formed as a result of the subducting Pacific and Philippine Sea plates 3). As such the long-term spatial distribution of volcanism needs to be estimated, not just for nuclear facilities but also as a precursor for the construction of hazard maps for natural disaster management. Over a long period of time, magma will either be fed to the surface many times via the same conduit resulting in a polygenetic volcano or once through a single dike generating a monogenetic volcano (Fig. 1). The spatial distribution of monogenetic volcanoes is much more difficult to estimate than for polygenetic volcanoes because the location of the next eruption forming a new volcano is different. Current knowledge of the complex geological factors and natural processes controlling the locations of monogenetic volcanoes is insufficient to estimate future spatial and temporal patterns. One way to estimate the future patterns of monogenetic volcanoes is through probabilistic analysis. Over the last two decades or so, probabilistic analyses have been used to construct probability maps showing the long-term spatial and temporal distribution estimates of future eruptions in several volcanic fields in the US and Mexico. One prominent example includes the Yucca Mountain Region (YMR); site of the US's proposed high-level radioactive waste repository which is located near approximately 40 basaltic vents formed since 10.5 Ma. Several key advances in probabilistic methods were developed through the study of the monogenetic and small polygenetic volcanoes in the YMR 4-6). The probability analyses are dependant upon the location and ages of vents, and have the added benefit of revealing, objectively, volcano alignments and clustering, in addition to estimates of the probability of eruption.

In Japan, much work has been focused on volcanic hazard analyses; the consequences of volcanic eruption but not on the probability of a volcanic eruption occurring in the first place. The purpose of this on-going research is to apply and improve on probabilistic models for estimating the future eruption patterns of monogenetic volcanoes. Two established probabilistic models based on point processes and one modified model are applied the Kannabe-Oginosen monogenetic volcano groups in the east San-in district (Fig. 2) and the Higashi-Izu monogenetic volcano groups distributed on the east part of the Izu Peninsula (Fig. 3).

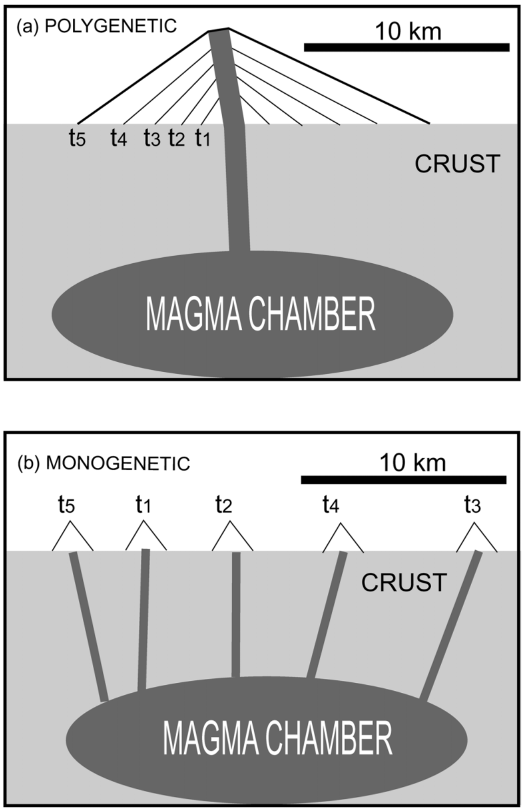

Fig. 1. **Simplified schematic diagrams depicting the difference between polygenetic and monogenetic volcanoes. (a) A polygenetic volcano is the result of periodic supplies of magma to the surface through the same conduit. (b) A new monogenetic volcano forms during each eruption event at a different location from the last because the magma supply path nearly always changes. Eruption events occur in time periods t1 to t5. The eruption periods (undefined) are considered relatively short compared to periods of non-volcanic activity.**

2. Probability estimates and models

The only attempts at long-term forecasting have been made on statistical grounds, using historical

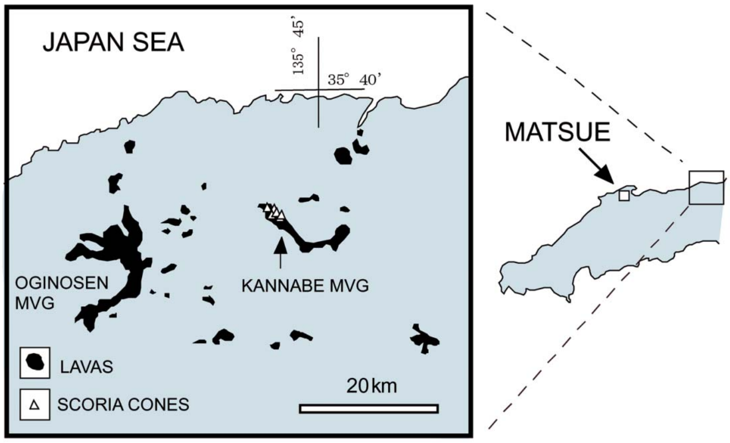

Fig. 2. Distribution of the Kannabe and Oginosen Monogenetic Volcano Groups and adjacent monogenetic volcanoes in the east San-in district (modified after Furuyama et al., 1993).

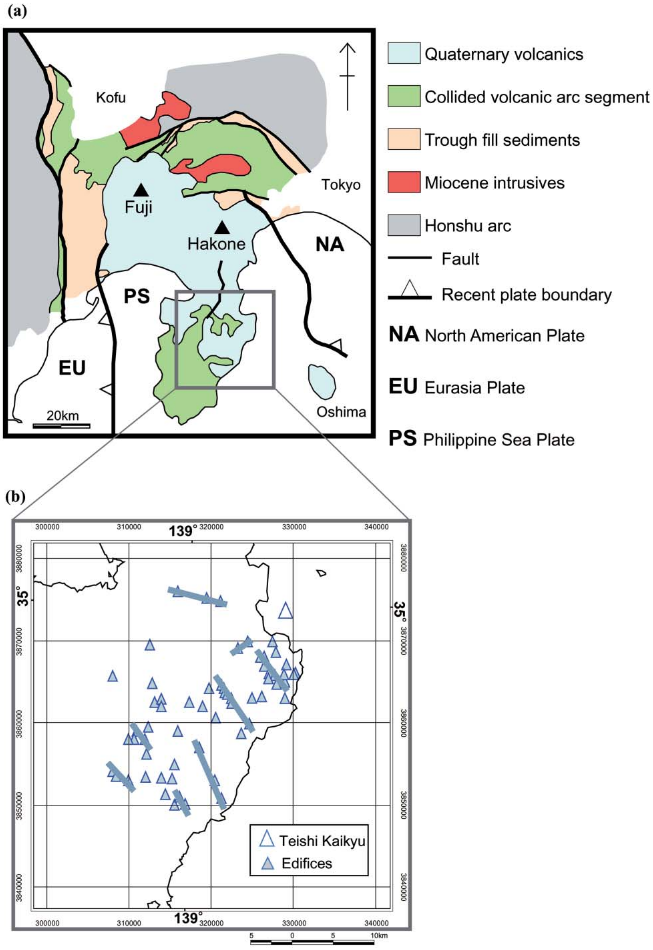

Fig. 3. Maps showing the location and tectonic setting of the Higashi-Izu Monogenetic Volcano Group (H-I MVG). The H-I MVG is located on the east part of the Izu peninsula near the boundary of three plates (a), and includes 59 edifices showing alignments of simultaneous eruptions in places (b). The location of edifices are known from the existence of scoria cones, tuff rings, lava domes and maars. The Teishi Kaikyu erupted off-shore, as recently as 1989. The predominant trend of the alignments is NW - SE (Hayakawa and Koyama, 1992; Koyama et al., 1995). This trend parrallels the orientation of maximum horizontal compression attributable to the subduction direction of the Philippine Sea plate.

records to examine eruption frequencies, types, patterns, risk and probabilities[4), 7-10)]. A volcanic eruption is the result of the supply of magma to the surface from a magma chamber. It will occur at some specific location (x, y) and within some time frame (t). Hence, there are two aspects of a volcanic eruption or 'event': (1) spatial, and (2) temporal. Previous volcanic activity has been used to estimate vent density (number of volcanic events per unit area) and recurrence rates (number of volcanic events per unit time). In other words, probability models rely on estimates of the expected regional recurrence rate and vent density of volcanism in order to calculate the probability of future eruptions. Most probabilistic models developed so far deal with either the spatial or the temporal aspects of volcanism. The most recent models deal with both, especially those applied to monogenetic volcano fields.

The choice of the probability model creates a variation in expected recurrence rate estimates and part of this variation is attributable to the definition of the volcanic event itself. The term' volcanic event' can vary considerably with author and it is worth dwelling on some of these definitions before proceeding with a description of the development of the probabilistic approach.

2. 1 Volcanic 'event' definitions

(1) Temporal

The temporal definition of a volcanic event ranges from a single eruption occurring in one day, to an eruption cycle or episode in which active periods of eruptions occur between dormant periods. The time scale of an active period may vary from several years to thousands of years. In the case of monogenetic volcanoes, the volcanic event is expected to be relatively short (months to years), and to occur only once. If there is more than one volcanic event at the same location, a 'monogenetic' volcano will become polygenetic. For example, some basaltic volcanoes in the YMR that were previously considered to be monogenetic (e.g. Lathrop Wells) have been re-classified as 'polygenetic' were more than one volcanic event at the same center have been shown to be separated by as much as several tens of thousands of years[11), 12)]. These types of 'monogenetic' volcanoes are also classified as 'compound' monogenetic volcanoes 13). In the case of probabilistic hazard assessment involving monogenetic volcanoes, and in particular spatial probability, a repeated eruption at the same vent would decrease the probability of an eruption in other areas.

(2) Spatial

The simplest spatial definition of a volcanic event for a monogenetic volcano is the existence of a relatively young cinder cone, spatter mound, maar, tuff ring or tuff cone. Such mapped edifices have been defined as volcanic events in several distribution analyses[5), 10), 14), 15)]. Older edifices, however, which may have been eroded and/or covered by sedimentary deposits such as alluvium are more difficult to locate, or could easily be overlooked. Radial dikes, near-vent breccias, or where there are no surface feature, magnetic and gravity data have been used as evidence for the existence of volcanic events by some authors[6)]. Several aligned edifices with the same eruption age should also be considered as a single volcanic event. Such vent alignments typically developed simultaneously as a result of magma supply from a single dike. For example the vent alignments in the Higashi-Izu MVG[16)], would be a single volcanic event. Where there is poor limitation in dating events (plus or minus 50,000 - 100,000 years), some authors have implemented a condition whereby a cone or cones can only be defined as a volcanic event if they are associated with a single linear or a dike system with more complex geometry[17)].

The definition of volcanic event is a source of uncertainty in any probabilistic hazard analysis. The choice is in reality limited to the amount and quality of the geological data available. In this paper, the existence of a surface manifestation such as a cinder cone, maar, tuff ring etc that formed in a period within 10,000 years with sufficient geological evidence is treated as a volcanic event.

2. 2 Recurrence rates

In order to estimate or predict the probability of volcanic eruption in a monogenetic volcano field (or polygenetic volcano) it is necessary to estimate the recurrence rate of volcanism up until the time of investigation. Such estimates are based mainly on geological field, chronological and geophysical data. In the case of monogenetic volcano fields, two rates need to be estimated in order to estimate the probability of a future eruption:

Temporal recurrence rate (time rate parameter)

λ_t= Number of volcanic events over a period of time (1)

Spatial recurrence rate (vent density)

$\lambda_{x,y}$ = Number of volcanic events in the volcanic field (2)

Observed λ_t values in the YMR range from two to 12 volcanic events per million years[4]. In the case of the Higashi-Izu Monogenetic Group in Japan, λ_t is even higher at one event per 7,900 years for during 40,000-150,000 years, and one event per 2,500 years for the last 40,000years[18]. Methods used to estimate these recurrence rates include plots of cumulative volume of volcanic events versus time[10, 11), 19)].

2. 3 Spatial characteristics of monogenetic volcanoes

In a typical monogenetic volcano field, a new edifice will form at a new location within or nearby the field itself during the long-term (10,000-200,000 years), whereas for a polygenetic volcano with a stable conduit, the location of the next eruption is expected to be the same during this time period. In this sense, the modeling of the future spatial patterns of monogenetic volcanoes is more significant than for polygenetic volcanoes during the 10,000 - 200,000 year time frame. As illustrated in Fig. 4, spatial characteristic features of monogenetic volcanoes include: (a) new volcanoes forming in locations different from existing volcanoes; (b) the tendency to cluster at a variety of scales; (c) the formation of vent alignments and shifts of alignments over a much longer period of time (usually of the order of millions of years). Alignments of monogenetic volcanoes are thought to be indicative of structural controls and are expected to reflect the orientation of principle horizontal stresses where ascending magmas exploit pre-existing structures[13]. It was shown that monogenetic volcanoes in the TransMexican volcanic belt paralleled high displacement rate structures, whereas polygenetic volcanoes aligned along low displacement structures[20]. Clustering on the other hand is thought to correspond to the location of melts beneath the surface or regions of higher magma supply to the surface than surrounding regions[5].

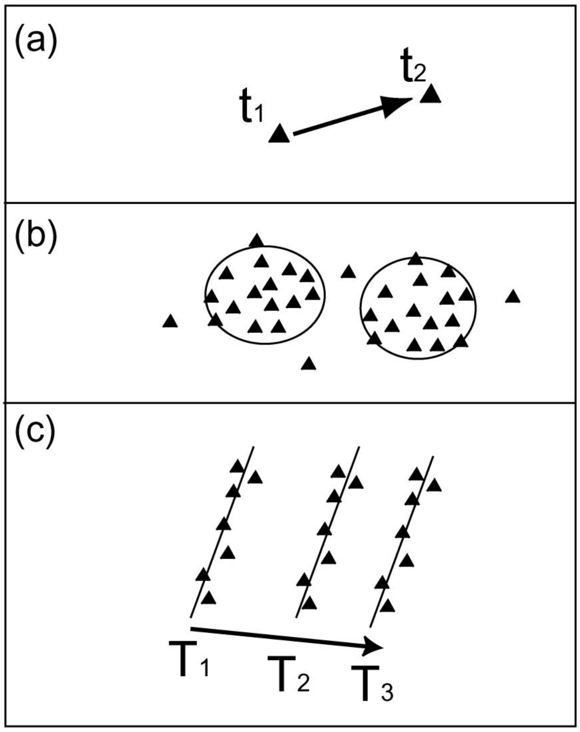

Fig. 4. **Simplified diagrams illustrating the common spatial characteristics of vent distribution in monogenetic volcano fields. New monogenetic volcanoes generally erupt in a new location (a). Clustering (b) and the formation of alignments (c) are ubiquitous in monogenetic volcano fields.**

2.4 Modeling the future long-term patterns of monogenetic volcanoes

Ideally, probabilistic methods must reflect at least the first two (Fig. 4) spatial characteristics of monogenetic volcanoes in order to give a reasonable estimation on the long-term future spatial patterns. Modeling the spatial characteristics of monogenetic volcanoes was first attempted in the YMR by applying models based on the homogeneous or 'simple' Poisson 4). However, it was pointed out that the simple Poisson approach required the allocation of zones with subjective boundaries to accommodate different recurrence rates in the volcanic field of interest 21).

The application of point processes 22-25) to model the long-term future patterns of monogenetic volcanoes has been argued as an appropriate technique and has seen widespread application 5), 14), 26), 27). The reason for this is that statistical point processes are sensitive to point clustering and point alignments. This method alleviates the need to define subjective zones within monogenetic volcanic fields which is needed for spatial homogeneous Poisson models. The resulting probability surfaces are continuous and are sensitive to clustering (i.e. the probability of eruption increases within clusters).

2. 4. 1 Spatial (S) Model

The most common and largely used point process model is based on the Kernel technique 28). This method was first applied to estimating vent density 5), 14). The local spatial recurrence rate is estimated using an Epanechnikov or Gaussian kernel function. A Kernel function estimates spatial variations in the intensity of volcanic events from the distance to nearby volcanoes and a smoothing constant h. The choice of kernel function is not as important as the choice of the smoothing coefficient as this has a much larger impact on spatial modeling of volcanic vents. The choice of the smoothing coefficient depends on a combination of several factors including size of the volcanic field, size and degree of clustering and the amount of robustness and conservatism required at specific points within or nearby the volcanic fields in question.

In this paper an Epanichnikov kernel function was chosen and several values of smoothing coefficient tested:

$$\kappa\left(p\right) = \frac{2}{\pi}\left(1 - \frac{d_i}{h}\right), \text{ if } \left(\frac{d_i}{h} < 1\right)$$

$$\kappa(p) = 0 \text{ , otherwise} \tag{3}$$

$\kappa(p)$is the kernel density function at point p, the location where density is estimated, and di is the distance between the ith vent and the point p.
The density of volcanic events is

$$\lambda_{x,y}(p) = \frac{1}{e_h}\sum_{i=1}^{n} h^{-2}\kappa(p) , \tag{4}$$

where n is the number of vents formed during the time interval and e_h is an edge correction. The edge correction compensates for the sporadic distribution and lack of point data at the edges of volcanic fields, in contrast to the relatively uniform distribution of point data at the centers. An edge correction set to unity results in a vent density distribution that is jagged at the edges of the volcanic field. A value of e_h is chosen such that the integral of equation (4) over the entire volcanic field yields 1. In most volcanic fields, the optimum value of e_h equals the number of volcanic events, n.

The local spatial recurrence rate estimation at each sample point is illustrated graphically in Fig. 5(a). Probability estimates are made for each point by multiplying the local spatial recurrence estimate with the temporal recurrence rate of the volcanic field:

$$P[\mathrm{N} \geq 1] = \lambda_{x,y}(p)\lambda_t ta \tag{5}$$

where N represents the number of volcanic vents that occur over time t and area a. This calculation is repeated on grid points throughout the volcanic field. The resolution is such that the spatial recurrence rate does not vary within each cell. Typical values of resolution range form 0.5 to 2 km.

Fig. 6 shows the results of applying the S model to the Higashi-Izu monogenetic volcano group. The maps show the distribution of the probability of one or more volcanic events occurring in the Hi-

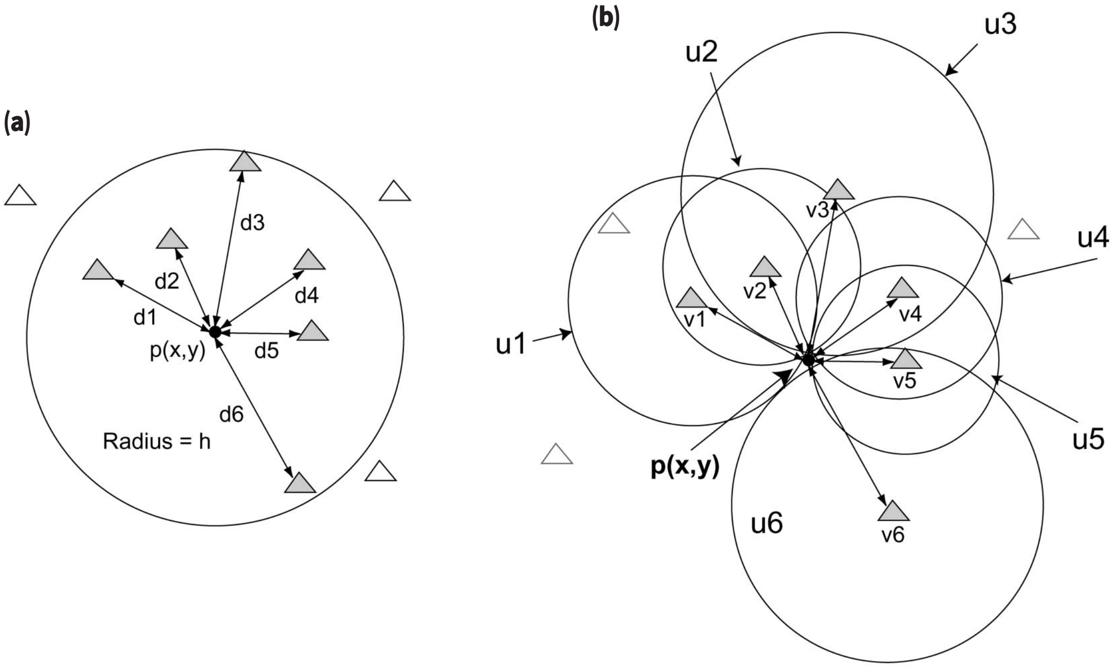

Fig. 5(a) Illustrating how local volcano density (local intensity) at each sample point p(x, y) is estimated using the Epanechnikov kernel function. The distances to the nearest volcanic edifices that fall within a circle of radius h are measured and summed.
(b) Diagram illustrating graphically the calculation of local volcano density with the spatio-temporal (S-T) nearest-neighbor method. Local intensity is calculated by summing the areas of circles centered over the locations of nearest volcano edifices multiplied by the age of the volcano.

gashi-Izu Monogenetic Volcanic Group for the next 10,000 years. Due to the higher temporal recurrence rate and increased number of vents, the probability of a new vent forming ranges from two to three orders of magnitude greater than that of the monogenetic volcano fields around the Yucca Mountain Site. For lower values of smoothing coefficient h, the probability tends to increase around the vents themselves whereas for larger values of smoothing coefficient, the probability distribution tends to cover a wider area but produce lower values near the vents.

In order to verify the most suitable values of the smoothing coefficient, probability distributions where recalculated using all edifices that formed before 20ka. Probability was calculated for the following 20,000 years to present using several values of smoothing coefficient. By comparing the distribution of the probability plots with subsequent vents that resulted after 20ka, it was found that smoothing coefficient values of 5 or 6km gave a better fit to the actual vent distribution during that period[29]. Carrying out a similar verification on pre 40ka vents it was found that probability distribution accuracy was maintained only for smoothing coefficient values greater than 8km. Since the verification using vents up until 20ka are more like related to modern day structures, values of 5 or 6km were considered to be more accurate values probabilistic calculations using the S model with the Higashi-Izu MVG[29]. For all values of h, the highest probability of one or more eruptions occurring in the next 10,000 years is distributed in the eastern part of the Higashi-Izu MVG. The highest probability ranges from 1×10^{-1} to 3×10^{-1}.

2. 4. 2 Spacio - Temporal (S - T) Model

One disadvantage with the S model is that the temporal recurrence rate does not vary locally, i.e. it is based on a regional estimation for the whole of the field. As such, vents with the most recent activity are weighted the same as vents with older ac-

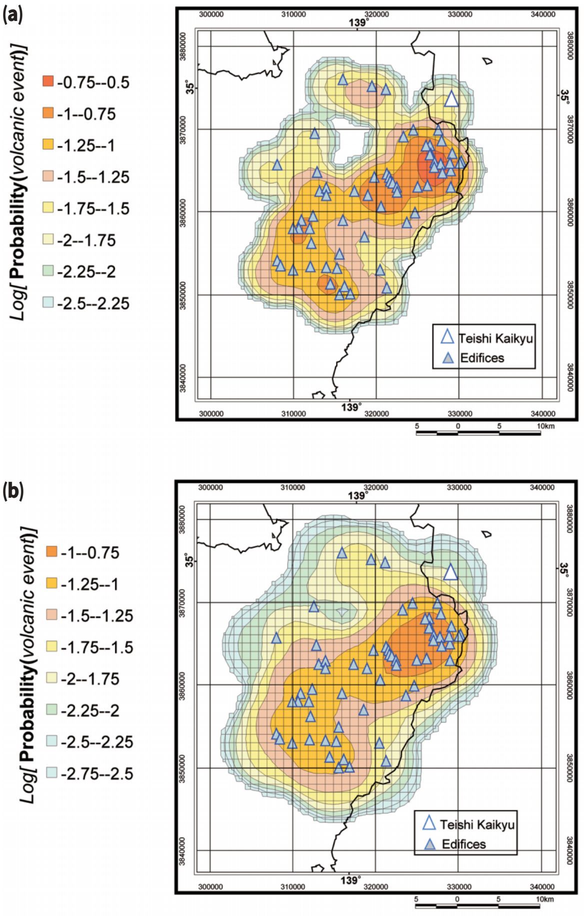

Fig. 6. Maps showing the probability of a new volcano forming during the next 10,000 years in the Higashi-Izu monogenetic volcano group calculated with the S model. The probability calculation used data from all vents and an observed recurrence rate of one eruption per 2,500 years with a smoothing coefficient h = 4 km (a) and h = 6 km (b). The probability of an eruption increases in the vicinity of vents for lower values of h.

tivity. Using a spatio-temporal statistical model based on nearest-neighbor methods [5), 24)], it is possible to include both the spatial and temporal rates locally on a grid. At each grid point local spatio-temporal recurrence rate is calculated as follows:

$$\lambda_{x,y,t}(p) = \frac{m}{\sum_{i=1}^{m} u_i t_i} \qquad (6)$$

where m nearest-neighbor volcanoes are determined as the minimum of , $u_i t_i$, t_i is the time elapsed since the formation of the ith nearest-neighbor vent, and u_i is the area of a circle whose radius is the distance between volcano i and point p, with $u_i > 1\text{km}^2$. This local spatio-temporal recurrence rate calculation is illustrated in Fig. 5(b). The sum of the calculated spatio-temporal recurrence rates gives an estimate to the overall regional recurrence rate. The calculated regional recurrence rate depends upon the number of nearest-neighbors used. As with the smoothing coefficient in the S model, the number of nearest-neighbors affects the resulting probability distribution. A number of nearest-neighbors should be tested so that the calculated regional recurrence rate approximates the observed regional recurrence rate based on geological and chronological data.

Probabilities are calculated from the recurrence rate values by using a Poisson distribution:

$$P[\mathrm{N} \geq 1] = 1 - \exp[-ta\lambda_{x,y,t}(p)], \qquad (7)$$

where t is the time interval of the probability estimate, a is the area about point p for which probability is estimated on the basis of recurrence rate at point p, and $\lambda_{x,y,t}(p)$ is the spatio-temporal recurrence rate estimate at point p calculated using equation (6) above.

Fig. 7 shows the result of applying the S-T model to the Higashi-Izu MVG. The age data of

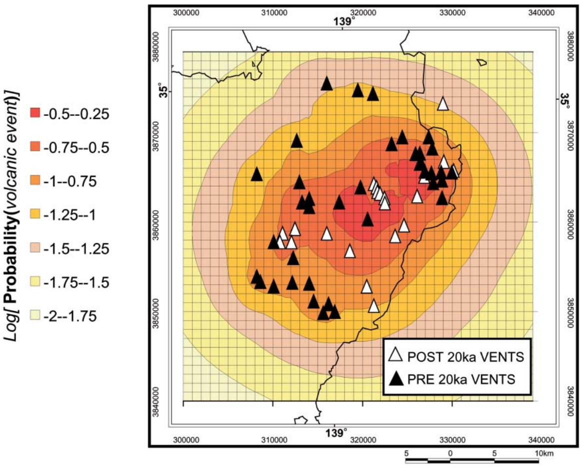

Fig. 7. Map showing the probability of a new volcano forming during the next 10,000 years in the Higashi-Izu monogenetic volcano group calculated with the S-T model and using data from all vents.

vents of monogenetic volcanoes was taken from previous works 16), 30). Based on comparisons with observed recurrence rates 16), it is estimated that S-T models using 12 to 15 nearest-neighbors give the closest approximation for the Higashi-Izu MVG. The highest probability of a new volcanic vent forming in the Higashi-Izu MVG in the next 10,000 years ranges from 3×10^{-1} to 5×10^{-1} (slightly higher than that of the S model). The distribution of the highest probability is located in the center of the volcanic field.

In the case of monogenetic volcano groups of the east San-in district, the observed regional recurrence rates during the Quaternary range from 1 to 4 vents per 100,000 years 31) which as with the Higashi-Izu MVG is higher than that of the YMR. Models with 9, 10, and 11 near-neighbors produced similar calculated recurrence rate estimates to that of observed regional recurrence rates in this region (vent age data from 31) and 32)). Probability plots (Fig. 8) based on 9 to 11 near neighbors yielded values slightly higher than that of the YMR, with highest probability values ranging from 1×10^{-2} to 3×10^{-2}, which is an order of magnitude lower than the highest probability value of the Higashi-Izu MVG.

2. 4. 3 Modified - Spatio - Temporal (M - S - T) Model

The probability models dealt with so far have place the highest probability value above current and past volcanic edifices. However, new eruptions are not expected to form at the current location of previous eruptions with monogenetic volcanoes. To this end, a modified spatio-temporal model (abbreviated as the M-S-T model here) was developed whereby the highest probability was located either side of previous vents at an orientation parallel to known shallow crustal features such as dikes or faults (Fig. 9). In the case of the Higashi-Izu MVG, maximum horizontal compression is known and is believed to be the origin of many of the NW-SE trending dikes 18), 33). Adding this trend into the M-S-T model and using the same number of nearest neighbors as in Fig. 7 yields the probability plot in Fig. 10(a). Both the highest and overall probability does not increase with the M-S-T model however the probability distribution changes 34). Compared with the S-T model, probability increases parallel to the length of the shallow structure and decreases either side of it.

The trend of maximum horizontal compression in the east San-in district is not as obvious as that for the Izu peninsula. Geophysical studies in the San-in region have placed estimates in the region of N40-70 °W 35), 36). In addition, lineaments and active faults in the vicinity of the Kannabe MVG have a predominant orientation of N60 °W. The alignment of volcanoes in the Kannabe MVG also has a similar trend. The probability map shown in Fig. 10(b) is the result of applying the M-S-T

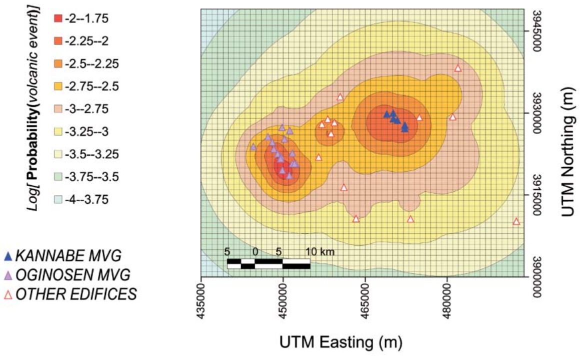

Fig. 8. **Map showing the probability of a new volcano forming during the next 10,000 years in the east San-in region calculated with the S-T model.**

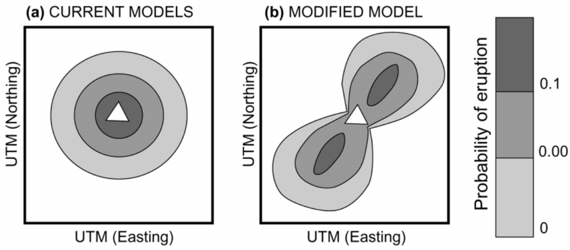

Fig. 9(a) In current models, the highest probability is centered on each volcano (white triangle).
(b) In the modified method, the highest probability is centered each side of current volcano along an orientation parallel to prevalent shallow structural features.

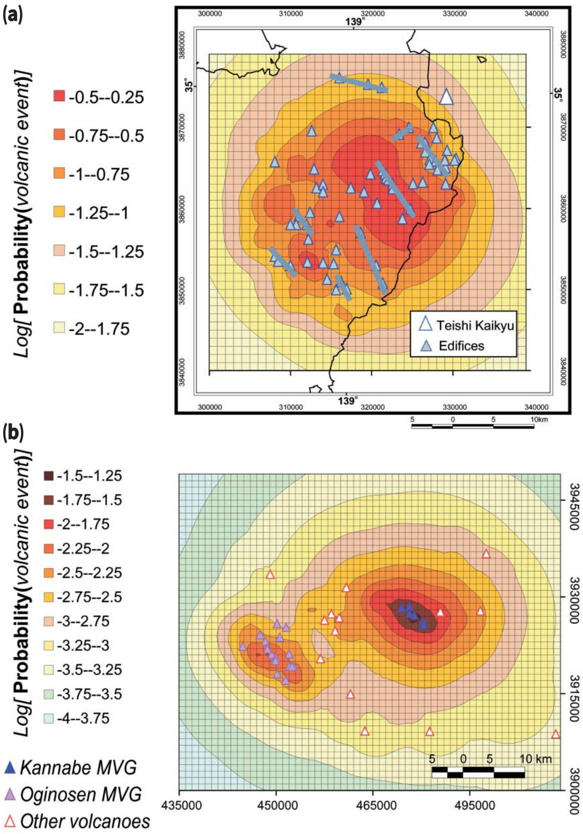

Fig. 10. Map showing the probability of a new volcano forming during the next 10,000 years in the (a) Higashi-Izu MVG and (b) Kannabe-Oginosen MVG calculated with the M-S-T model.

model to the E-San in district with using an alignment/lineament trend of N60 ℃W. Compared with the S-T (Fig. 8) model, the distribution changes slightly and probability increases in the region around the Kannabe MVG.

3. Summary

Point processes are presently the most feasible tools for probabilistic modeling of the long-term future patterns of monogenetic volcanoes because such processes are sensitive to vent clustering and vent alignments. Three probability models based on point processes were applied to the Higashi-Izu and Kannabe-Oginosen MVG:

(1) The S model which estimates probabilities based on the location of vents, the regional recurrence rate of the volcanic field and a smoothing coefficient. For the Higashi-Izu MVG suitable values of smoothing coefficient range from 6 to 9km and resulting highest probabilities of one or more volcanic events occurring in the next 10,000 years range from 1×10^{-1} to 3×10^{-1}.

(2) The S-T model estimates probabilities based on both the locations and ages of vents. For the Oginosen-Kannabe MVG the highest probability of a volcanic eruption occurring in the next 10,000 years ranges from 1×10^{-2} to 3×10^{-2} and that of the Higashi-Izu MVG ranges from 3×10^{-1} to 5×10^{-1}.

(3) The M-S-T model is a modified version of the S-T model that has been adapted to included orientations and lengths of shallow structural features such as dikes, lineaments and/or active faults. Probability values do not change too significantly but the probability distribution does.

Overall, the estimated probability of one or more volcanic events forming is higher in the Higashi-Izu MVG than the Kannabe-Oginosen MVG. These values are in turn slightly higher than calculated probabilities in the YMR (approximately 40 monogenetic volcanoes)[5),6)] but lower than values for large fields such as the Springerville volcanic field, Arizona which contains at least 366 volcanic events[26)].

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