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Eruption Pro 10.5 – the new and improved long-range eruption forecasting software

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ABSTRACT. **The software package, ERUPTION Pro 10.5 performs a statistical analysis on loaded volcano eruption data from both historical and current real-time or near real-time data. This report presents further updates since the previous report on ERUPTION Pro 9.6. ERUPTION Pro 10.5 has been most favourable in its analysis capability, rendering accuracy better than 90% since the incorporation of newer, improved algorithms beginning in late 1997, 2002 and 2004.**

1. INTRODUCTION

Forecasting the time, place, and character of a volcanic eruption is one of the major goals of volcanology. It is also one of the most difficult goals to achieve. An experimental computer programme, specifically designed for the MS-DOS and Windows based PCs (Trombley, 1990) has been developed and tested over the past fourteen years in an attempt to forecast long-range volcanic eruptions. The intent of the ERUPTION Pro 10.5 software package is to forecast the next eruption event of volcanoes about the world. This software programme is intended as an additional forecast aid and diagnostic tool, and is not intended as the definitive concept in forecasting an eruption of any particular volcano. It should be kept in mind that the software package ERUPTION Pro 10.5, at this point, is in no way infallible and a prediction is only as good as the data used in creating it. The term 'forecast' is used as it lends itself to a more probabilistic and less precise connotation of a precise scientific prediction, which has the connotation of precision. The current state-of-the-art in the discipline of volcanic forecasting is far from precise. Furthermore, forecasting as used by ERUPTION Pro 10.5 has the notion of 'may or probably' and not will erupt.

This new application programme primarily uses the fundamental concept of the Poisson distribution paralleling the pioneering works of Wickman (1966) and De La Cruz-Reyna (1991). The disciplines of the programme ERUPTION Pro 10.5 have been thoroughly described previously (Trombley 2002).

2. DEFINING ERUPTIONS AND LONG-RANGE FORECASTS

Whenever the discussion of volcanoes arises, the subject of eruptions is inevitable. But just what constitutes an eruption of a volcano becomes a valid point and is, of course, of concern and importance to input data for ERUPTION Pro 10.5.

In the 2nd Edition of *Volcanoes of the World*, by Simkin and Siebert (1993), an eruption is defined in the following manner, "*The arrival of volcanic products at the Earth's surface is termed an eruption*." Further, they go on to say, "*... we confine the term to events that involve the explosive ejection of fragmental material, the effusion of liquid lava, or both*." This is also the premise for ERUPTION Pro 10.5 and only eruptions that produce pyroclastic materials, liquid lava or ash are considered and entered into the database. Input data sources concerning the type of eruption, and relevant data are principally provided by three sources of data: 1, Simkin and Siebert (1993), the account record as reported and published in the *Volcanoes of the World*; 2, the *Bulletin of the Global Volcanism Network* (Smithsonian Institution); and 3, direct reports from actual visits and reports from various volcanic observatories and other responsible volcanic reporting agencies around the globe.

With respect to ERUPTION Pro 10.5's long-range forecasting ability, the term "long-range" used herein refers to forecasting at least one or more years in advance of an eruption event.

3. THE POISSON DISTRIBUTION MODEL

The Poisson distribution is a good model for describing phenomena where the probability of occurrence is small and constant. It arises as the model underlying various physical phenomena such as is the case with volcanic eruptions, which involve time. It is also an approximation where the number of trials, $\boldsymbol{n}$, is large as is the case of volcanoes where hundreds and even thousands of years pass before an eruption. The probability of success (an eruption), $\boldsymbol{p}$, is small. In other words, the Poisson distribution is an excellent distribution for rare events. As De La Cruz-Reyna (1991) states, "*If one concludes that well-sampled moderate-to-large magnitude sequences follow a Poisson distribution, then the basic features of Poissonian processes become fundamental in understanding the physics of volcanism. The analysis of published global data supports the notion that occurrence of eruptions can be accurately described as a simple Poisson process*."

4. The Binomial Distribution Model

Shield volcanoes present a different diagnostic problem than do strato, complex, and compound volcanoes in that they do not follow a Poisson distribution. But shield volcanoes are similar to other types of volcano in that they either are erupting or not erupting. It appears that a Binomial distribution might be the best distribution fit for shield volcanoes.

For shield volcanoes, we consider a set of n mutually independent trials each made under these conditions and ask for the probability of exactly r successes (eruptions) and $n - r$ failures (no eruptions). Each of these independent trials is, of course, a binomial distribution. Each trial is independent so the probability of a specific sequence, e.g., starting off with r successes followed by $n - r$ failures is $p^r q^{n-r}$. However, the order of the sequence is irrelevant. Any order of eruption (or non-eruption) events will do, and each possible order has the same probability of occurring, $p^r q^{n-r}$.

We must, therefore, multiply this probability by the number of ways n trials can be divided into r successes (eruptions) and $n - r$ failures (no eruption). This number is ${}_nC_r$, and the overall probability is

$$P_{n,p}(r) = \frac{n!}{r!\,(n-r)!}\, p^r q^{n-r} \quad \text{................. (1)}$$

Where $P(r)$ = Probability of an eruption, p = Probability of eruption on any one trial, q = Probability of no eruption on any one trial

5. Revised Probabilities

Revising probabilities when new information is obtained is an important part of probability analysis. Often, as is the case with most volcanoes assumed to be Poisson distributed, the initial or prior probability estimates are completed for a specific event of interest, i.e., the probability of an eruption for the current year. Then, some new additional information is obtained, a missed eruption, or the fact that another year transpires and there has been no eruptive event. Given this new information, the prior probabilities are updated by calculating the revised probabilities referred to as posterior probabilities. Bayes' Theorem provides a means for making such calculations. This theorem, along with the axioms suggested by combining the Poisson and negative binomial distributions and using a Bayesian analysis, as they apply to volcanic eruptions (Ho, 1990), have been incorporated into ERUPTION Pro 10.5.

When the Poisson process as applied to volcanic eruptions is expanded to accommodate a gamma mixing distribution on λ, there becomes an immediate consequence of this mixed Poisson model. The frequency distribution of eruptions in any given interval of equal time follows a negative binomial distribution. The probability of x eruptions becomes:

$$P(x) = \frac{\Gamma(r + x)}{\Gamma(r)\, x!} [\alpha/(\alpha+1)]^{\Gamma}\ [1/(\alpha+1)]^{x}\ ,\ x = 0, 1, 2, \text{......... (2)}$$

where $\mathbf{r}$ and $\boldsymbol{\alpha}$ are the shape and scale parameters of the gamma distribution respectively.

Treating the average eruption rate λ as a random variable means that the probability distribution function $\mathbf{f(x, \lambda)}$ is, in reality, a conditional probability. The condition being that λ is in state λ. Therefore, when using a probability distribution for λ, it is more suitable to use the notation $\mathbf{f(x|\lambda)}$ for the data $\mathbf{x}$. From the conditional distribution of $\mathbf{x}$ and the given (calculated) prior distribution for λ, the joint distribution of $\mathbf{(x, \lambda)}$ can be calculated.

$$f(x,\lambda) = f(x|\lambda)g(\lambda) \quad \text{.................. (3)}$$

where $\mathbf{g(\lambda)}$ is the probability density function and the marginal or absolute distribution of $\mathbf{x}$, with probability:

$$P(x) = E_g[f(x, \lambda)] = \int f(x|\lambda)g(\lambda)d\lambda \quad \text{...... (4)}$$

For the volcanoes being monitored by ERUPTION Pro 10.5, and assuming that λ follows a gamma distribution, then

$$g(\lambda) = \frac{\alpha^{\Gamma}\, \lambda^{\Gamma-1}\, e^{-\alpha\lambda}}{\Gamma(r)}\ ;\ l > 0;\ r, \alpha > 0 \text{......... (5)}$$

where $\mathbf{r}$ and α are the shape and scale parameters respectively as previously mentioned, and

$$g(x|\lambda) = \frac{e^{-\lambda}\, \lambda^{x}}{x!} \qquad x = 0, 1, \text{......... (6)}$$

Therefore, from Equation 4 above, the absolute probability for the number of eruptions per unit of time interval is given by,

$$P(x) = \int_0^\infty \frac{e^{-\lambda}\lambda^x}{x!} \frac{\alpha^r}{\Gamma(r)} \lambda^{r-1} e^{-\alpha\lambda} d\lambda$$

$$= \frac{\Gamma(r + x)}{\Gamma(r)\, x!} [\alpha/(\alpha+1)]^r \; [1/(\alpha+1)]^x, \quad x = 0, 1, 2, \ldots \quad (7)$$

The mean and variance for the negative binomial distribution are given by:

$$E(x) = r/\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

and

$$\text{Variance}(x) = r(\alpha + 1)/\alpha^2 \quad \ldots\ldots\ldots (9)$$

The incorporation of the combined negative binomial and Poisson distributions along with the Bayesian analysis has had a positive effect on the statistical forecast accuracy of ERUPTION Pro 10.5. The increased performance can be observed from the results of essentially two factors; a) the incorporation of the Bayesian analysis and b) the updated volcano eruption data incorporated into the software. These factors alone appear to have improved the forecasting ability of ERUPTION Pro 10.5.

Table 1 presents the entire forecasting results through year 2004 (February). The years prior to 2004 were completed with the earlier versions of ERUPTION Pro. What is significant is the increase in accuracy forecasting since the incorporation of the Bayesian analysis along with the other improvements, e.g., real-time or near real-time component contributions to the probability analysis.

Table 1. ERUPTION Pro Analysis History

Year	Accuracy %	Notes
1989	52.50	1
1990	23.08	
1991	62.96	
1992	12.82	
1993	29.73	
1994	28.21	
1995	10.53	
1996	61.29	2
1997	85.71	3
1998	94.12	
1999	93.62	
2000	90.39	
2001	90.91	4
2002	92.00	
2003	90.70	
2004	100.00*	5

[1]Initial Eruption Pro 1.0. [2]Incorporation of Bayesian analysis (EPro 8.5). [3]Volcano Freq. Of Erupt. analysis added (EPro 9.6). [4]Release of Eruption Pro 10.4. [5]Release of Eruption Pro 10.5. *To February, 2002.

Another improvement factor built into ERUPTION Pro 10.5 is the eruption event count. Although a particular volcano may erupt more than once during a given year, ERUPTION Pro 10.5 counts only the fact that the volcano erupted at least once in the year of analysis.

5. Probability Contributions

In addition to the normal probability contribution in ERUPTION Pro 10.5 from the historical data, there are several other contributions that contribute to the overall analysis. Those other contributions are: Input from Correlation Spectrometer (COSPEC), Thermal Imaging, Volcanic-Seismicity, Deformation and the volcano's Frequency of Eruption analysis. The following discusses their input and how the contribution is used in ERUPTION Pro 10.5

6. Remote Measurements of SO_2 Fluxes

Many active volcanoes release gases to the atmosphere both during and between eruptions. The main gas species emitted are H_2O, CO_2, H_2S, SO_2, H_2, CO, CH_4, HCl and HF, the relative proportions of which can be related to thermodynamic (temperature-pressure-oxygen) conditions. The COSPEC is a portable spectrometer which measures the absorption of solar ultraviolet light by means of SO_2 molecules.

6.1. SO_2 Flux Data

The SO_2 flux data currently supplied by COSPEC measurements are commonly used: 1) to constrain the mass of magma that is degassing and 2) to correlate with the level of activity. They are therefore suitable data for long time monitoring (Symonds *et al.*, 1994). In this section, we will focus our attention on point 2.

6.2. SO_2 Emisions and Volcanic Activity

Volcanoes emit measurable SO_2 fluxes in conditions of low explosivity, effusive activity, dome or intrusion or open-vent degassing (Symonds *et al.*, 1994). Table 2 displays typical SO_2 fluxes measured at 17 volcanoes showing different state of activity between 1984 and 1991. Stoiber (1973) suggested a classification of SO_2 emitters, with small (< 200 t/d), moderate (200-1000 t/d) and large (> 1000 t/d) emitters. Moderate and large SO_2 fluxes are considered as coming from magma degassing (Symonds *et al.*, 1994).

Table 2. Volcanic-Seismicity to Probability Conversion

Factor	VT	Hybrids	LP
0.00	0	HY<10	LP≤10
0.10	0<VT≤5	10<HY≤40	10<LP≤50
0.11		40<HY≤80	50<LP≤100
0.12	Etc.	80<HY≤120	150<LP≤200
0.20	5<VT≤30	10<HY≤40	10<LP≤50
0.21	Etc.	40<HY≤80	50<LP≤100
0.30	30<VT≤50	10<HY≤40	10<LP≤50
0.31	Etc.	40<HY≤80	50<LP≤100
0.40	40<VT≤75	10<HY≤40	10<LP≤50
0.41	Etc.	40<HY≤80	50<LP≤100

6.3. Long Time-Series

As most of SO_2 flux data are sporadic measurements performed over more or less short periods, it is interesting to observe really long-time continuous monitoring, such as those performed at Galeras (Columbia) from 1989 to 1995 (Zapata *et al*., 1997) or Soufriere Hills (Montserrat, West Indies) in 1997 (Watson *et al*., 2000). At Galeras, low SO_2 fluxes were recorded after the May 1989 eruptions, indicating the presence of a shallow and partially degassed magma or a conduit that was partially closed. On the contrary, the very large SO_2 fluxes from September 1989 to March 1990 indicated that the magma was undegassed and the conduit was open (Zapata *et al*., 1997).

Recent measurements have demonstrated that SO_2 fluxes were correlated with deformation rates and bulk volcanic-seismicity. Watson *et al.* (2000) showed that at extrusive domes-type volcanoes, SO_2 emission rates were supposed to fluctuate as the result of various processes operating (release of gas through the dome and conduit, flow-retardation in free-spaces in dome, direct release, dome cracking by extrusion of magma, dome disruption by pyroclastic flows. On this type of volcano, this leads to potentially very variable fluxes. At Soufriere Hills, SO_2 eruption rates are highly correlated with ground deformation in periods of high hybrid (mixed VT and LP events) volcanic-seismicity. At this volcano, SO_2 flux, tilt amplitudes and hybrid volcanic-seismicity clearly increased during the 4 days prior to the dome collapse on 25th June, 1997.

6.4. Correlation Spectrometer (COSPEC)

COPEC readings are obtained from the various observatories and other official volcanic reporting agencies throughout the world as the readings are made and become available. ERUPTION Pro 10.5 compares the nominal readings with the actual readings taken from the volcano under analysis. The comparison is performed from a ratio format from which the probability contribution is determined. For instance, the Soufriere Hills volcano on Montserrat has a nominal COSPEC reading of 450 tonnes per day output. The current actual reading is 640 tonnes per day. Therefore the ratio is calculated as:

$$R_{COSPEC} = \frac{COSPEC_{actual}}{COSPEC_{nominal}} = \frac{640}{450} = 1.42 \quad \text{.........} \ (10)$$

As the COSPEC reading waxes and wanes, so does the ratio and therefore the probability contribution. The software programme is safety interlocked at a maximum of 0.300 and a minimum of 0 as a probability contribution due to COSPEC.

6.5. SO_2 Conclusion.

Many SO_2 flux measurements have been performed at active volcanoes. Evidence of the relationship between emission rates and activity are available in the literature. At most volcanoes, high variations of the SO_2 emission rate are recorded prior, during and after eruptions. Because exsolution of volatiles is controlled by many factors (permeability, pressure, viscosity, porosity), changes prior to eruptions can be either increases or decreases, according to the type of volcanoes, the feeding system, and the dynamics of the volcano. Within this frame, volcanoes working with active domes should be considered as the most complex systems to monitor with SO_2 flux measurements.

6.6. Thermal Imaging

The latest addition to the probability contribution suite is the input due to an increase on thermal output from the volcano under analysis. This is accomplished through satellite based thermal imaging. Input for this contribution is obtained from the Geostationary Operational Environmental Satellite (GOES) namely, GOES-8, GOES-9, GOES-10, the Operational Significant Events Imagery (OSEI), and the Advanced Very High Resolution Radiometer (AVHRR) satellite imaging. Images are analyzed, along with reports concerning the volcano being examined, and assigned a sliding scale probability contribution factor ranging from 0 to 0.1 probability. The sliding scale is predominantly based on the colour interpretation of the examined images. e.g., a light yellow image would receive an assignment of 0.05 whereas a red image would receive a 0.1 probability value. Care is taken so as not to confuse reflectivity of clouds, etc. and otherwise false images from being interpreted as a thermal probability contribution.

6.7. Volcano Seismicity

Seismicity plays an important and major role in the probability determination relative to a volcano's potential (probability) of having an eruptive event. It is, arguably the largest contributor to the probability calculations.

Table 2 contains values of the number of Long Period (LP), Volcano-Tectonic (VT), and Hybrid values. Based on these received, real-time values, or combinations therein, a scaled value, ranging from 0 to 0.5 probability contribution for a particular volcano, is determined and entered into the software package's database.

6.8. Deformation

As with other contributions, ground deformation plays a role in the probability determination of an eruption. Ground deformation on volcanoes may be due to several causes. These include: (a) inflation/deflation of a buried magma storage zone, (b) injection of a dike or sill which may or may not be an eruption conduit, (c) subsidence due to lava loading, gravitational settling, or spreading of the entire volcano, and (d) slope movement caused by slope creep prior to failure or by magma pressure variations on steep slopes. Combinations of these causes frequently occur to produce a complex pattern of deformation.

ERUPTION Pro 10.5 utilizes the results of the Mogi model (Mogi, 1958) in its analysis. The Mogi model predicts that

$$\Delta d = \frac{3a^3Pd}{4\mu(f^2+d^2)^{3/2}} \qquad \text{.................. (11)}$$

$$\Delta h = \frac{3a^3Pf}{4\mu(f^2+d^2)^{3/2}} \qquad \text{.................. (12)}$$

where: **a** = the radius of the source sphere, **P** = change in hydrostatic pressure in the sphere, **f** = depth to the centre of the sphere, μ = Lame's constant, **d** = radial distance on the surface from a point above the source, **Δd** = radial horizontal displacement at the surface, **Δh** = vertical displacement of a point at the surface.

The input to the software is in the form of a sliding scale function based on the received displacement with a minimum of 0 and a maximum of 0.2. As the deformation reading changes, so does the probability contribution.

6.9. Volcano Frequency of Eruption

The most improved probability contribution is due to the analysis of a volcano's frequency of eruption. Since the conception of ERUPTION Pro in 1989, the Volcano Frequency of Eruption Analysis (VFEA) has been tracked. This contribution uses the simplest of probability models namely;

$$P = \frac{k}{h} \qquad \text{.................. (13)}$$

where: **k** = number of outcomes (eruptions), **h** = number of possible outcomes (last 10 years).

For example, since 1992, volcano Hekla, located in Iceland, has erupted once. Using Equation 13, this means that the probability contribution for volcano Hekla is 0.100 for the current year's forecast.

7. Reliability Analysis

As with any new or experimental software package, particularly in the case of volcanic eruption forecasting, there is a need to perform an analysis to determine if the model is accurate and if the methodology proposed has sound footing. A reliability analysis was performed per se in the original paper on ERUPTION Pro (Trombley, 2002) with mixed accuracy results (See Table 1 for accuracy results). However, a retroactive model testing analysis has been performed for 1998 thru 2002 which reveals (to date) a 92.7% overall accuracy level.

Table 3 illustrates the calculated reliability analysis for the years 1998 through 2002 (to date). In previous versions of ERUPTION Pro, the analysis yielded an average, considering all years from 1989 through 1997, an overall reliability of 71.7%. This means that previous versions of ERUPTION Pro will be incorrect 28.3% of the time. To date, the new and improved version of ERUPTION Pro's reliability to correctly and accurately forecast volcanic eruptions shows that it will be incorrect 7.3% of the time (or would be correct 92.7% of the time)

8. Shortcomings

Even with the success of ERUPTION Pro 10.5, there are a few shortcomings of the software. Arguably, the largest is the lack of available data on all the volcanoes that the software monitors. It is however, an unrealistic expectation to have all volcanoes (particularly those volcanoes that are

Table 3. Reliability Analysis Results (* as of February, 2004). λ = failure rate, f(t) = probability density function, F(T) = probability of failure, R(T) = probability of success, where, λ = no. of failures / no. of volcanoes for 1 year, $f(t) = \lambda e^{-\lambda t}$ $t \geq 0$, $F(T) = 1 - e^{-\lambda t}$ & $R(T) = 1 - F(T) = e^{-\lambda t}$

Year	No. of Years	No. of Volcanoes	No. of Failures	λ	f(t)	F(T)	R(T)
1998	1	36	3	0.083	0.077	0.080	0.920
1999	2	48	3	0.063	0.059	0.061	0.939
2000	3	54	4	0.074	0.069	0.071	0.929
2001	4	45	4	0.089	0.081	0.085	0.915
2002	5	51	4	0.078	0.073	0.075	0.925
2003	6	44	2	0.045	0.043	0.044	0.956
2004*	7	18	0	0.000	0.000	0.000	1.000
Totals:		**296**	**20**	**0.068**	**0.063**	**0.065**	**0.935**

very remote) monitored to the degree necessary for very accurate forecasting results. There is simply not the equipment, money and personnel to encompass such an endeavour. Another shortcoming is the timeliness of current acquired data. In some cases, the data received and confirmed on various volcanoes are almost immediate, in other cases, it may be a day or two before data are received and confirmed.

There are other probability contributions that may be considered as potential inputs to ERUPTION Pro 10.5, but are not currently in the software. For example, the monitoring of crater lake temperature (for those volcanoes that have crater lakes) is not input to the software, but is currently being explored. Additional analysis of output gasses is another area of probability contribution that may be considered although SO_2 analysis is currently considered. Lastly, the analysis of volcanic plumes, and the measurement of gas fluxes in plumes, may also be a viable contribution.

9. Conclusions

The current state-of-the-art in the science of volcanic forecasting is far from precise. However, ERUPTION Pro 10.5 has seemingly made great strides in its ability to reasonably forecast volcanic eruption events. With the current and latest improvements, ERUPTION Pro 10.5 appears to be heading in the proper direction. Although ERUPTION Pro has been in development for fourteen years now, it is much too early (only the last six years are being considered) to consider the software valid for volcanic hazard prediction or disaster mitigation by the general public at this time. It should only be used as an indication that an eruption event may occur with respect to all known and relevant data. Further testing of ERUPTION Pro 10.5 will be undertaken in the next few years to test its ability in eruption forecasting ability.

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