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Time-Distance Relationship between Volcanic Eruptions and Large Earthquakes in Central Japan: A Statistical Analysis

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Abstract

Analysis of large earthquake (magnitude, $M \geq 7.0$) and volcanic data reveals that most of the large earthquakes that occurred in Japan are preceded by volcanic activity. Correlation coefficients show that the relationship between earthquakes and eruptions ($r = 0.999$), and time and log distance ($r = -0.94$) are highly significantly correlated ($P < 0.0001$). The time-distance relationship between major eruptions and large earthquakes are shown by the model, $Y = 44.31 - 16.40 \log(X)$, where Y and X indicate time (duration of time from the starting year of a major eruption to the occurrence time of the earthquake) and distance (distance from the volcano to the epicenter of the shock), respectively. Statistical analysis based on the relation shows that eruption occurs in earlier times prior to the concerned shock if the epicenter of the earthquake is nearer to the respective volcanic activity. This relation is recognized by various statistical testing procedures. Based on the relation, the crustal breaking time in the estimated epicenter should be known. This suggests that eruptions may be triggered by the stress generated from the epicentral region. The increased regional strain may squeeze up magmas before breaking the crust. If this is true then the occurrence time of the shock may follow a major eruption.

Key words: Time-distance relationship, volcanic eruptions, large earthquakes, epicenter, model validation.

1 Introduction

Japan is frequently affected by earthquakes. Nearly one tenth of the earthquakes on the earth occur in or around the Japanese islands. Large interplate earthquakes occur along the plate boundaries off the Pacific coast of the Japan islands. Interplate earthquakes within the continental plate take place in the upper crust beneath the Japanese islands and along the coast in the Sea of Japan. It is a widely accepted idea that most large, shallow earthquakes along island arcs result from active subduction and collisions among four lithospheres plates (Pacific plate, North American plate, Eurasian plate and Philippine Sea plate) in this region (Ishida, 1989; Seno et al., 1993, 1996).

Tectonic strain accumulates in the lithosphere of the pre-seismic stage and is released by the shocks (Kimura, 1978). Nakamura (1975) suggested that contractual strain generated by regional crustal stress around a magma reservoir can squeeze up magma within an open conduit, causing a summit eruption on one hand and the formation of dike resulting in flank eruptions through the increase of core pressure on the other hand. If the eruptions are influenced by the regional tectonic stresses causing earthquakes, some spatial and temporal relations between large interplate earthquakes and eruptions can be expected along the island arc systems.

A number of researchers have pointed out possible relationships that existed between eruptive activity and seismic activity since early times, although nobody can be sure about the physical mechanisms connecting the volcanic activities with seismicity. McGregor (1949), for instance, inferring from statistical studies, suggests that a temporal relation exists between the local seismic activity and volcanic eruptions in the Caribbean volcanic arc. Such local seismic activity is thought to be directly involved in volcanic eruptions. Through his studies around the Japanese and New Hebrides areas, Blot (1956; 1972) showed that the deep seismic activity migrates from a greater depth to a shallower one and finally results in volcanic eruptions (Blot process). On the basis of statistical and worldwide studies, Latter (1971) states that Blot process would probably be a secondary phenomenon and that the relationship would be primarily the correlated sequence of seismic and volcanic events resulting from periods of tectonic instability and perhaps increased tensional conditions which affect very wide areas of the earth's surface for periods of several months to several years at a time. On the other hand, many scientists have pointed out that there exists some physical relation between volcanic activity and tectonic seismicity (Tokarev, 1971; Yokoyama, 1971; Kaminuma, 1973). Thus, the purpose of the study is to develop that physical relationship between volcanic activity and tectonic seismicity in the central Japan.

2 Data and Method

The area selected in this paper is based on available data. Scientific studies of volcanoes have been going on since the nineteenth century in Japan (Suwa, 1970). The data on eruptions and large earthquakes with magnitude of $M \geq 7.0$ are taken from the secondary sources: (i) *the Catalogue of Active Volcano of the World Including Solfatara Fields*, IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior); (ii) *the Bulletin of Volcanic Eruptions*, Volcanological Society of Japan, (IAVCEI); (iii) *the List of the Worlds Active Volcanoes*, Special Issue of Bulletin of Volcanic Eruptions; (iv) Tokyo Astronomical Observatory (*Science Almanac*) (v) Meteorological Office, and (vi) some published papers on volcanic eruptive activities. Epicenters of the large earthquakes are mainly taken from JMA data, and the work of Kimura (1994) and Seno (1977a, 1978). The focal mechanism solutions of the large earthquakes suggest low-angle thrust faulting and sometimes strike slip faulting. Active volcanoes and their related large earthquakes with magnitudes, durations and lengths of all events from epicenters to volcanoes are shown in Table 1.

Table 1. Active volcanoes and their related large earthquakes in central Japan. Distance (km); Distance from a volcano to the epicenter of the earthquake, Y(year); Time duration between major eruption and large earthquake, and Magnitude; Magnitude of the large earthquake.

No.	Volcano Volcano	Eruption year	Earthquake year	Magnitude Magnitude	Distance (km)	Y(Year)
1	Fujisan	864	878	7.4	50	14
2	Hachijo	1487	1498	8.4	130	11
3	Miyake	1595	1605	7.9	120	10
4	Oshima	1600	1605	7.9	160	5
5	Hachijo	1605	1605	7.9	450	1
6	Oshima	1684	1703	8.1	40	19
7	Fujisan	1707	1707	8.4	350	1
8	Oshima	1846	1854	8.4	170	8
9	Fujisan	1854	1854	8.4	430	1
10	Bayonnais	1906	1909	7.5	430	3
11	Oshima	1912	1930	7.9	50	18
12	Oshima	1912	1923	7.9	70	11
13	Miyake	1940	1944	7.9	270	4
14	Bayonnais	1946	1946	7.9	420	1
15	Bayonnais	1946	1953	7.4	290	7
16	Oshima	1950	1953	7.4	230	3
17	Bayonnais	1952	1953	7.4	290	1
18	Miyake	1962	1972	7.2	180	10
19	Miyake	1962	1971	7.1	190	9
20	Miyake	1962	1978	7	80	16

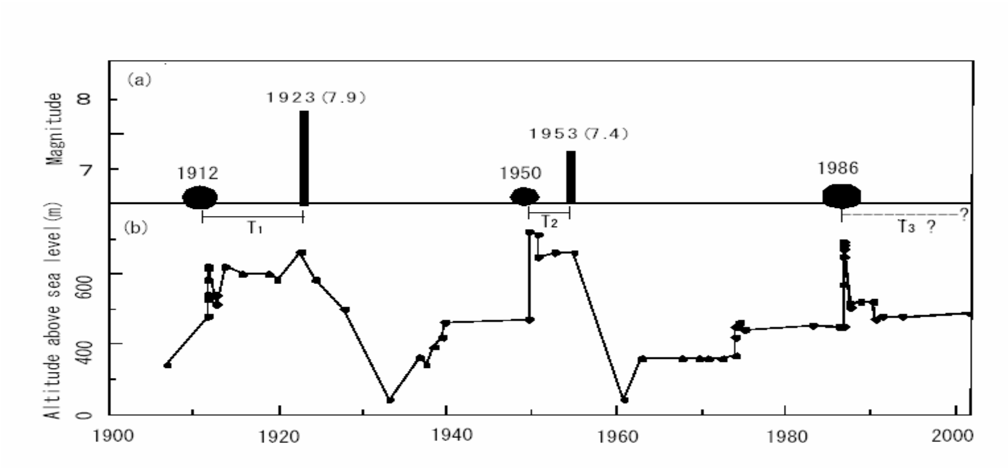

Fig. 1. Relationship between large eruptions (dots) and change in level of floor of summit crater of Mihara-yama (line), and large earthquakes (vertical bars) that have occurred along the Sagami Trough. (a) Record of large earthquakes and eruptions along Sagami Trough; (b) Change in levels of floor of the summit crater of Mihara-yama (after Kimura, 1976). T_1 and T_2 show the duration of time interval between eruptions of Izu-Osima volcano and occurrence of the shocks of 1923 and 1953, respectively. T_3 indicates unknown duration of time for the future event.

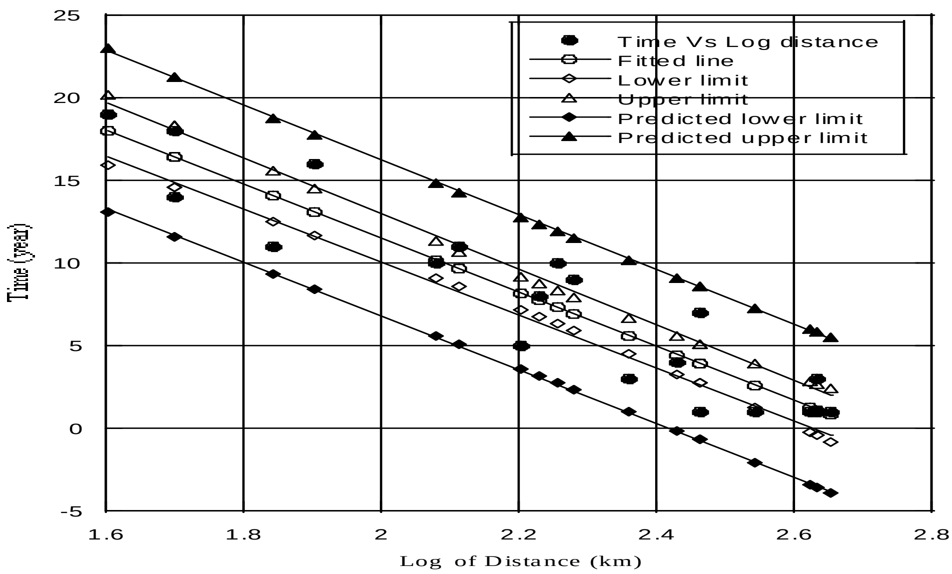

Fig.2. Time - distance relationship between volcanic eruptions and large earthquakes in central Japan. Scattered diagram (bold circle), fitted line (open circle), confidence interval for the mean response (lower limit; open square, Upper limit; open triangle) and prediction interval for the future observation (lower limit; bold square, Upper limit; bold triangle) are shown.

3 Model Building and Statistical Analysis

Regression analysis is a statistical technique for investigating and modeling the relationship between variables. Applications of regression are numerous and occur in almost every field. In fact, regression analysis may be the most widely used statistical technique. We have a number of sample observations on Time and Distance between eruptions and epicentre of large earthquakes in Japan (Table-1). Plotted observations (Fig. 2) suggest that there is a strong statistical relationship between Time and log Distance; in fact, the impression is that the data points generally, but not exactly, fall along a straight line. If we let Y represent Time and X represent log Distance, then the equation of a straight line relating these two variables is

$$Y = \beta_0 + \beta_1 X \tag{1}$$

where β_0 is the intercept and β_1 is the slope. Now the data points do not fall exactly on a straight line, so eq.(1) should be modified to account this. Let the difference between the observed value Y and the straight line ($Y = \beta_0 + \beta_1 X$) be an error ε. ε is a statistical error that is, it is a random variable ($\varepsilon \sim NID(0, \sigma^2\ )$) that accounts for the failure of the model to fit the data exactly. Thus, a more plausible model for the time-distance data is

$$Y = \beta_0 + \beta_1 X + \varepsilon \tag{2}$$

Figure 3 indicates a strong linear relationship between the time of start of errruptions (X) and the time of occurrance of major earthquakes (Y). This also suggests a similar model like (2).

3.1 Estimation of parameters by using least square method

Suppose that n observations are available. The parameters β_0, and β_1 are unknown and must be estimated using sample data. For models in which some transformation of any function is linear in the parameters, least square estimation can be used to estimate the parameters of the model. That is, we will estimate the parameters in eq. (2) so that the sum of squares of the differences between the observations (Y) and the straight line is a minimum. If the errors are normally and independently distributed with mean zero and constant variance (σ^2), the unknown parameters of the above models can be estimated using least square method as: $\hat{\beta} = (X'X)^{-1}X'Y$, where $\hat{\beta}$ is a vector of order 2x1, X is a matrix of order nx2 and Y is a vector of order $n \times 1$.

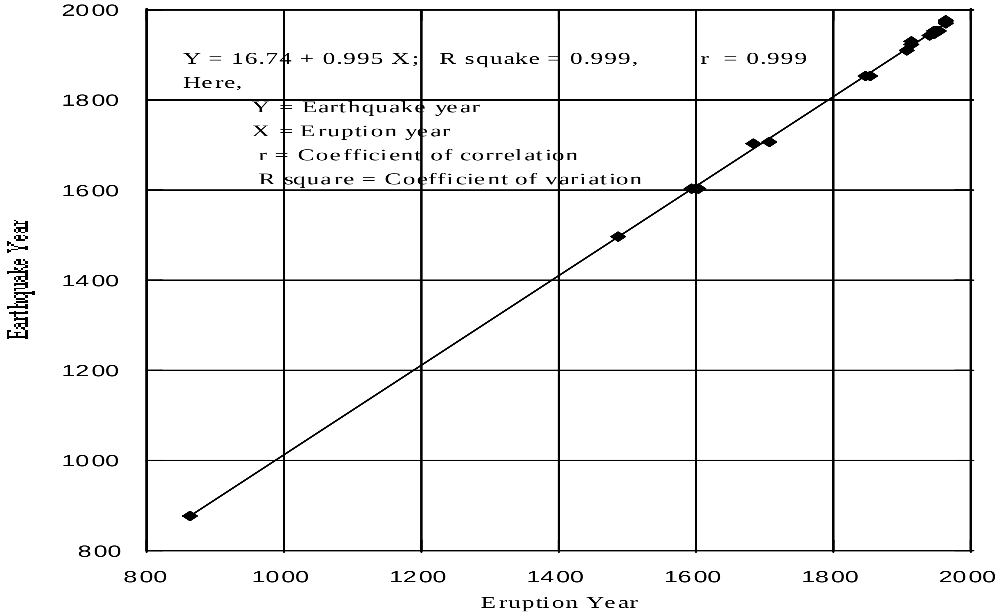

Fig. 3

Fig. 3. Scatter diagram with the fitted model between eruptions and earthquakes.

3.2 Test for significance of regression

The test for significance of regression is a test to determine if there is a linear relationship between the response Y and the regressor variable X. This procedure is often thought of as an overall test of model adequacy. The appropriate hypotheses are

$$\begin{aligned} H_0 &: \beta_1 = 0 \\ H_1 &: \beta \neq 0 \end{aligned} \tag{3}$$

Rejection of this null hypothesis implies that X contributes significantly to the model. If the null hypothesis is true, then SS_R (sum of squares regression)$/\sigma^2$ follows a χ^2_k distribution, which has the same number of degrees of freedom as number of regressor variables in the model. Also SS_{Res} (sum of squares residuals)$/\sigma^2 \sim \chi^2_{n-k-1}$ and that SS_R and SS_{Res} are independent. By the definition of F statistic

$$F_0 = \frac{SS_R/k}{SS_{Res}/(n-k-1)} = \frac{MS_R}{MS_{Res}} \tag{4}$$

follows the $F_{k,n-k-1}$ distribution. Where n is the total number of observation, $k(k = 1)$ is the number of parameter, MS_{Res} and MS_R represent the mean sum of square residual and mean sum of square regression, respectively. A test of size α for the null hypothesis is given by rejecting H_0 if $F_0 > F_{\alpha;k,n-k-1}$, where $F_{\alpha;k,n-k-1}$ denotes the α percentage point of the F-distribution with k and $n-k-1$ degrees of freedom.

3.3 Test on individual regression coefficients

The hypothesis for testing the significance of any individual regression coefficient, such as β_j are

$$\begin{aligned} H_0 &: \beta_j = 0 \\ H_1 &: \beta_j \neq 0 \end{aligned} \tag{5}$$

If $H_0 : \beta_j = 0$ is not rejected, then this indicates that the regressor X_j can be deleted from the model. The test statistic for this hypothesis is $t_0 = \{\hat{\beta}_j - E(\hat{\beta_j})\}/se(\hat{\beta}_j) \sim t$-distribution with degrees of freedom (n-k-1). The null hypothesis $H_0 : \beta_j = 0$ is rejected if $|t_0| > t_{\frac{\alpha}{2},n-k-1}$. Here, $t_{\frac{\alpha}{2},n-k-1}$ denotes the value of the t distribution such that $Pr(t > t_{\frac{\alpha}{2},n-k-1}) = \frac{\alpha}{2}$. $k(k = 1)$, n, se and α are the number of parameters, number of sample observations, standard error and level of significance, respectively.

3.4 Test for correlation coefficient

The sample correlation coefficient is a measure of the linear association between Y and X. The estimator of the population correlation ρ is the sample correlation coefficient $r = \frac{S_{XY}}{\sqrt{(S_{XX}SS_T)}}$, where S_{XX}, SS_T and S_{XY} is the sum of squares X, sum of squares total and sum of the products of X and Y, respectively. It is often useful to test the hypothesis that the correlation coefficient equals zero, that is

$$\begin{aligned} H_0 &: \rho = 0 \\ H_1 &: \rho \neq 0 \end{aligned} \tag{6}$$

The appropriate test statistic for this hypothesis is, $t_0 = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$ which follows the t distribution with degrees of freedom $n-2$ if $H_0 : \rho = 0$ is true. Therefore, we would reject the null hypothesis if $|t_0| > t_{\frac{\alpha}{2},n-2}$, where n and α are the number of sample observations and level of significance, respectively.

3.5 Confidence interval estimation

The width of the confidence intervals of the parameters is a measure of the overall quality of the regression line. It the errors are normally and independently distributed, then the sampling distribution with some transformation follows t distribution with n-2 degrees of freedom. Therefore, a 100(1-α)% confidence interval of the regression coefficient is given by

$$Pr\{\hat{\beta} - t_{\frac{\alpha}{2},n-2}se(\hat{\beta}) \leq \beta \leq \hat{\beta} + t_{\frac{\alpha}{2},n-2}se(\hat{\beta})\} = 100(1-\alpha) \tag{7}$$

These confidence intervals have the usual frequency interpretation. That is, if we were to take repeated samples of the same size at the same α levels and construct, for example, 95% of those intervals will contain the true value of the parameters. The limits of the parameters depend on the value of α (level of significance).

4 Time-distance relationship between volcanic activity and seismicity in central Japan

Activity of Izu-Oshima volcano is directly related to the occurrence of great Kanto earthquake in 1923 and Boso-oki earthquake in 1953 along the Sagami Trough. The altitude of Aburatsubo area in southern Kanto was dropped before the earthquake of 1923 and 1953. Since the land mass dropped, the floor of the summit crater of Izu-Oshima volcano rose as much as 400 m, and the volcano erupted. The earthquake occurred almost concurrently. The crater's floor fell when the land of southern Kanto area rose again after the earthquake. It is suggested that the increased compressional crustal stress along the trough squeezes up magma beneath Mihara-yama, and that consequently, the large earthquake occurs to release compressional strain along the trough (Fig. 1). This activity is regarded as a contributing factor to both a major eruptions and earthquakes (Kimura, 1976).

T_1 and T_2 in Fig. 1 represent time intervals between major eruptions and earthquakes as shown in Table 1. We noticed the variation of time intervals T_1 and T_2 between major eruptions and earthquakes. This occurs because variations of time intervals strongly suggest that the crustal strain migrates from the area where crustal rupture may appear in future; this was pointed out using all of the related eruptions and large earthquakes in central Japan (Kimura, 2003).

Activity of volcanic eruptions, epicenters, magnitudes and distribution of seismic intensity of large earthquakes were examined to justify the time-distance relationships observed by Kimura (1994). We used this to provide a testing ground for statistical modeling and analytical procedures to understand more precisely the time-distance relationships between volcanic eruptions and large earthquakes in central Japan. In this paper, a simple linear regression model is fitted to investigate the time-distance relationships between volcanic eruptions and large earthquakes.

Coefficient of determination (R^2) is approximately 0.88 that is 88% of the variability in Time (Y) is accounted for by the regression model. Table-2 presents the analysis of variance test for overall significance of regression. Failing to reject the null hypothesis (eq.(3)) implies that there is no linear relationship between Time and log distance. On the other hand, rejection of null hypothesis implies that log distance is of value in explaining the variability in Time. However, rejection of null hypothesis could mean either that the log linear model is adequate or that even though there is a log linear effect of distance. Results in Table-2 suggest that the overall regression is highly significant ($P < 10^{-7}$) indicating Time may have a significant relationship with log distance. However, this does not necessarily imply that the relationship found is an appropriate one for predicting Time as a function of log distance. Further tests of model adequacy are required.

Table 2. Analysis of variance test. Table gives the mean squares of regression and residual along with F statistic for testing $H_0 : \beta_1 = 0$. P-values are used for hypothesis testing. The P-value for the test for significance of regression is reported as P=0.00 (this is a rounded value; the actual P-value is less than 10^{-7}).

Source	Sum of Squares	Degrees of Freedom	Mean Square	Test Statistic (F_0)	P-value P-value
Time-Distance model					
Regression	585.09	1	585.09	129.29	0.000
Residual	81.46	18	4.52		
Total	666.55	19			
Earthquake-Eruption model					
Regression	1321910	1	1321910	34658.08	0.000
Residual	686.55	18	38.14		
Total	1322597	19			

Table 3. Table shows the standard errors of the estimates and intercepts along with the t statistic for testing $H_0 : \beta_0 = 0$, and $H_0 : \beta_1 = 0$. The P-values for the test for significance of individual regression coefficients are reported. 95% confidence intervals for the parameters are also shown. LB and UB are the lower and upper limits of the parameters, respectively.

Predictor	Coefficients	Standard Error	Test Statistic (t_0)	P-value	95% Confidence Interval	
					LB	UB
Time-Distance model						
Constant	$\hat{\beta}_0$=44.31	3.26	13.60	0.00	37.46	51.15
Log distance	$\hat{\beta}_1$=-16.40	1.44	-11.37	0.00	-19.43	-13.37
Earthquake-Eruption model						
Constant	$\hat{\beta}_0$=16.74	9.61	1.74	0.01	-3.45	36.93
Eruption	$\hat{\beta}_1$=0.999	0.005	-186.17	0.00	0.98	1.01

We performed tests on individual regression coefficients (Table-3) to determine whether log distance has a significant influence on time-distance relationship. Since absolute value of the test statistic $t_0 (t_0 = -11.37)$ in Table-3 is greater than the true value of $t (t = 2.101)$, we may reject $H_0 : \beta_1 = 0$ and conclude that log distance or X, contributes significantly to the model. We also investigated the influence of other focal parameters (Focal depth, Intensity and Magnitude) to the model but we did not find any significant influence of the focal parameters on the model except log distance.

The negative value of the coefficient β_1 indicates that the eruption occurs prior to the concerned shock if the epicenter of the earthquake is nearer to the respective volcano/volcanoes. Table 3 shows the 95% confidence intervals for the parameters of the models. That is, if we choose repeated samples of the same size then 95% of those intervals will contain the true value of the parameters.

The correlation coefficients between Time and log distance (r = -0.94), and earthquakes and eruptions (r = 0.999) are highly correlated ($P < 0.001$) and significantly linearly related (Figs. 2-3). Other pairs do not show any significant correlation (Table-4). The Variance Inflation Factor (VIF = 1.001) suggests that all the data sets used in the analysis are free from multicolinearity. Outliers and the effects of autocorrelation on the data sets were also tested. Thus, the fitted models are:

$$\text{Time} = 44.31 - 16.40 \log(\text{Distance}); \quad R^2 = 0.878 (\text{Fig. 2})$$

$$\text{Earthquake} = 16.74 + 0.995 \text{Eruption}; \quad R^2 = 0.999 (\text{Fig. 3})$$

Table 4. Correlation coefficients among distance, earthquake, eruption, magnitude and time. The double asterisk '**' indicates that correlation between the variables is significant at 1% level.

	Log Distance	Earthquake	Eruption	Time	Magnitude
Log Distance	1.000	0.34	0.36	-0.94**	0.08
Earthquake		1.00	0.99**	-0.21	-0.19
Eruption			1.00	-0.23	-0.18
Time				1.00	-0.16
Magnitude					1.00

'**' Correlation is significant at the 0.01 level (2- tailed)

5 Model Validation

To check the validity of the fitted models we have computed the RCVPP (Restricted Cross Validated Predictive Power) and shrinkage (Khan and Ali, 2002, and Stevens, 1996). The RCVPP is defined as

$$\begin{aligned} \rho^2_{cv} &= 1 - \frac{(n-1)(n-2)(n+1)}{n(n-k-1)(n-k-2)}(1-R^2);\ R^2 \geq 1 - \frac{n(n-k-1)(n-k-2)}{(n+1)(n-1)(n-2)}; \\ &\quad n > k+2 \\ &= 0, \quad \text{otherwise.} \end{aligned}$$

where n is the sample size, k is the number of predictors in the regression equation and the cross-validated R is the correlation between observed and predicted values of the dependent variable. Using the above statistic, it can be concluded that if the prediction equation is applied to many other samples from the same population, then $(\rho^2_{cv} \times 100)\%$ of the variance on the predicted variable would be explained by the regression equation (Stevens, 1996; p. 100).

Estimated cross validity predictive power, ρ^2_{cv}, of the predicted equation are respectively 0.9988 and 0.857. These results show that for any independent sample from the same population more than 99% of the variance on the predicted earthquake and 85% of the variance on the predicted time interval would be explained by the proposed equations. In other words, the expected amounts of shrinkage of R^2 for earthquake prediction is very small implying highly cross validated. Also, the stability of the fitted model can be computed as $\tilde{\eta} = 1 - \tilde{\xi}$, where $\tilde{\xi}$ is the shrinkage (Stevens, 1996) can be computed as $\tilde{\xi} = |\rho^2_{rcv} - R^2|$. We have $\tilde{\eta}$ is equal to 0.979 for Fig. 2 and 0.999 for Fig. 3 implying that over the population the fitted model in Fig. 2 is 97.9% and that in Fig. 3 is 99.9% stable.

6 Discussion and conclusions

A probable relationship between volcanic activity and large earthquakes was first shown in the Kanto area when Izu-Oshima volcano was in active stage and a few years later the two earthquakes occurred concurrently in that region (Kimura, 1976). Based on this information we build up a model to verify the time-distance relationship between volcanic activities and large earthquakes in the area of central Japan, and obtained a significant relationship between them (Figs. 2-3). Results of the analysis for linear regression model are shown in Tables 2-4 and Figs. 2-3. All results suggest that volcanic activity and occurrence of large earthquake is closely related to the change of stress activity. The nearest volcano of the epicentral area may be affected earlier by the migration of accumulated strain and erupted first. Consequently, other volcanoes are affected and erupted by the same way according to distance. In general, when the volcanoes are erupted, enough strain accumulated in the eventual epicentral region following earthquakes.

In conclusion it is provided that the criterion for occurrence of large earthquake based on timing of a volcanic eruptions has a time-distance relationship. That is, volcanoes nearer to the eventual epicentral region erupts earlier than the others. This result strongly suggests that time-distance relations may help to predict an earthquake before it strikes if the epicentral location can be identified in advance and if the activity of the volcanoes is well monitored.

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