Clock Advance in Earthquake Triggering of Volcanic Eruptions

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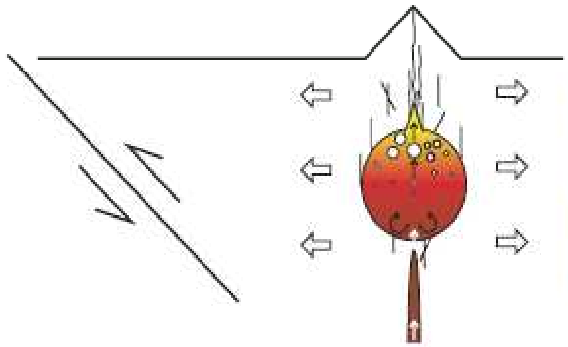
Models for E/Q Triggering of Volcanic Eruptions

- Static elastic stress/strain dilatation peturbs magma plumbing system (Barrientos 1994).

- Walter and Amelung (2007):

How earthquakes may trigger eruptions



Unclamping
Dike formation and propagation
Volatile exsolution
Density and viscosity decrease
Bubble growth
Mingling of different magmas
Magma ascent and depressurization

- Postseismic effects from viscoelastic response of crust and mantle compression and shear peturbations (Marzocchi et al 2002)

E/Q Triggering of Volcanic Eruptions

Linde and Sacks (1998)

Remote dynamical triggering of eruptions due to passing of seismic waves.

8 cases post-1900

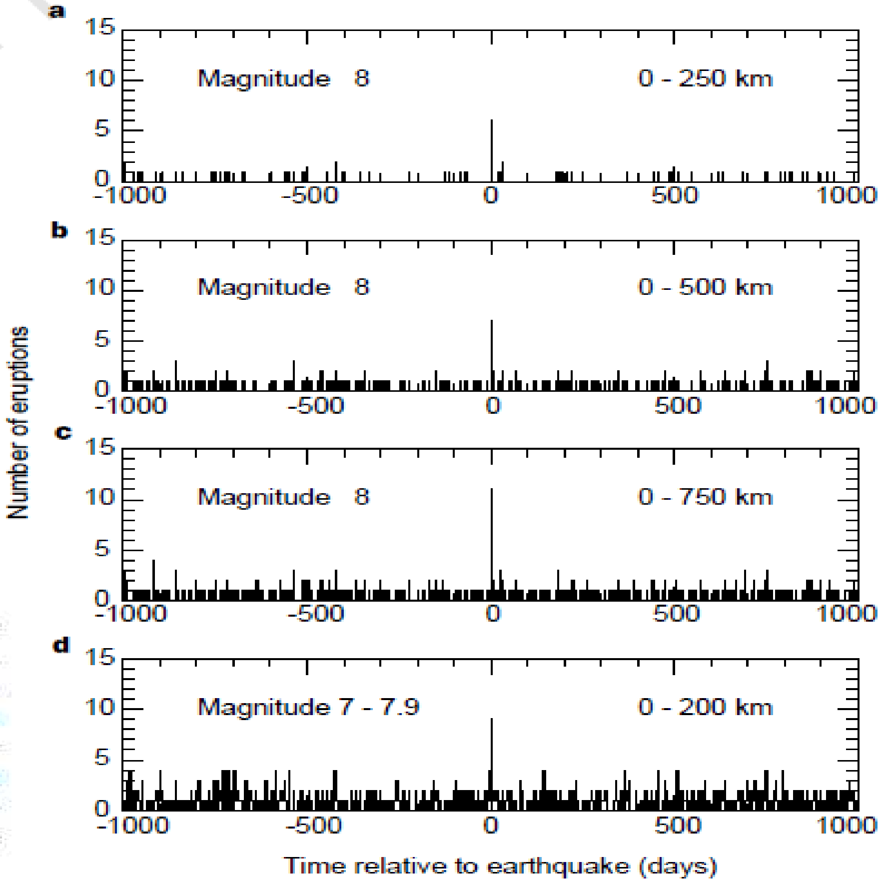
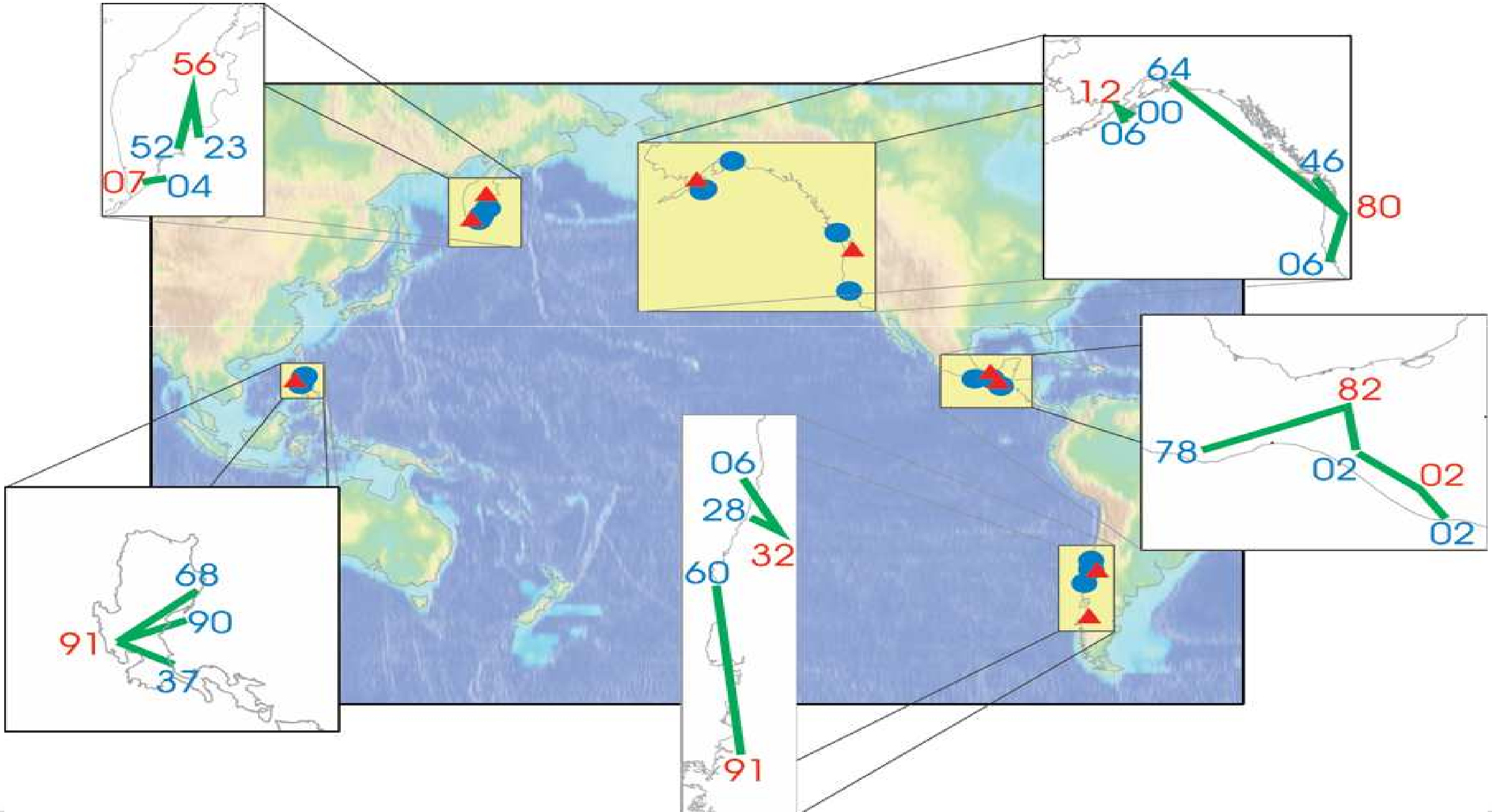


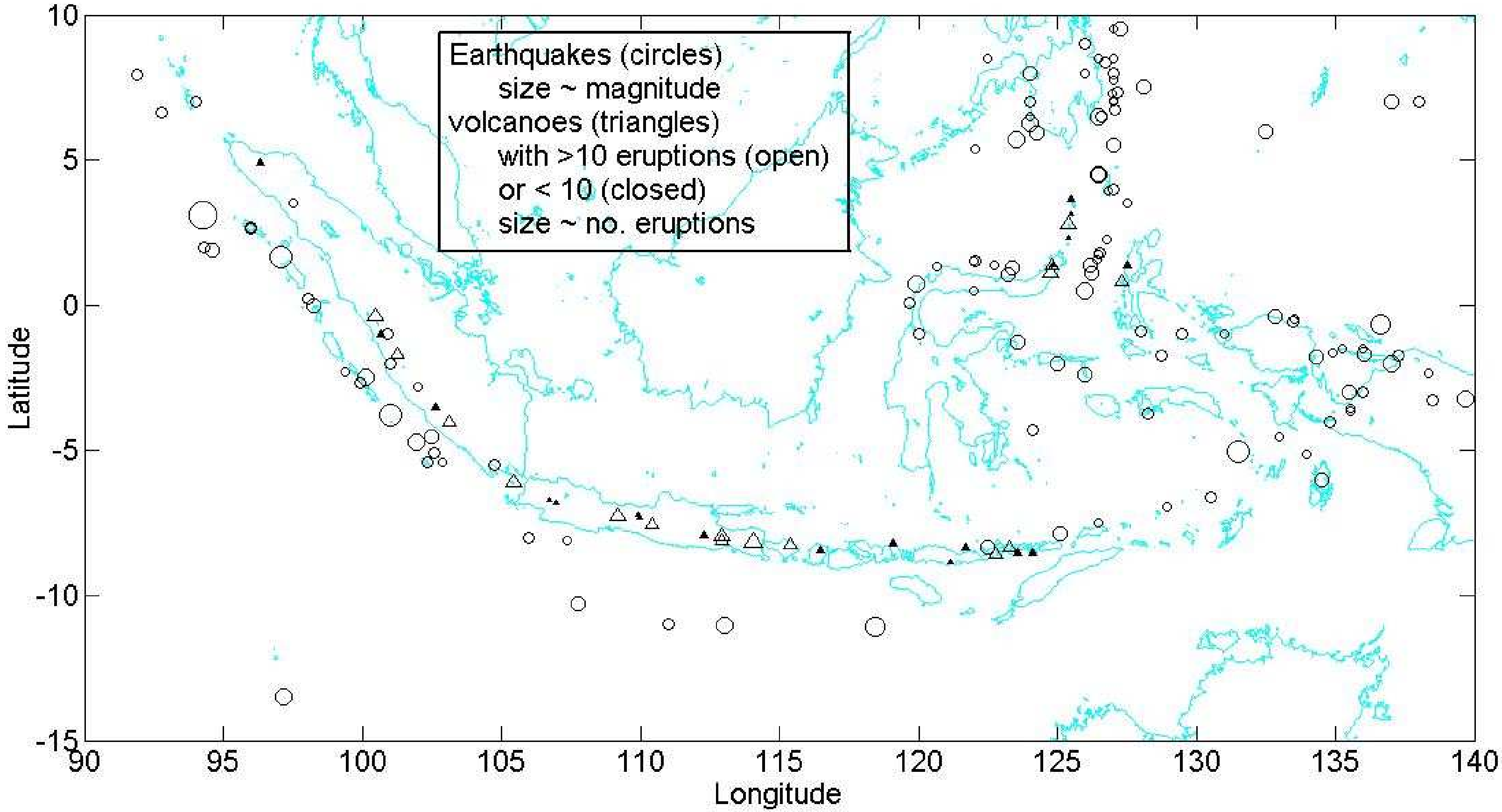
Figure 1 Histograms of number of eruptions occurring within ±1,000 days of large earthquakes. In **a**, **b** and **c**, the eruptions, following earthquakes of magnitude >8, are grouped in 1-day bins; **a**, **b** and **c** are for earthquake–eruption distances of up to 250 km, 500 km and 750 km, respectively. The large peak for the bin following the earthquake is evidence for a triggering effect, although there is no evidence for triggering in the distance range 250–500 km. In **d**, the eruptions following earthquakes of magnitude 7–7.9 are grouped in 2-day bins for the distance range 0–200 km. Most of these eruptions are at distances >100 km. All other time bins display expected random values.

Delayed Triggering

‘Peturbation’ models allow for delayed triggering (Marzocchi et al, 2002)



E/Qs and Volcanoes of Indonesia



E/Qs and Volcanoes of Indonesia – Completeness?

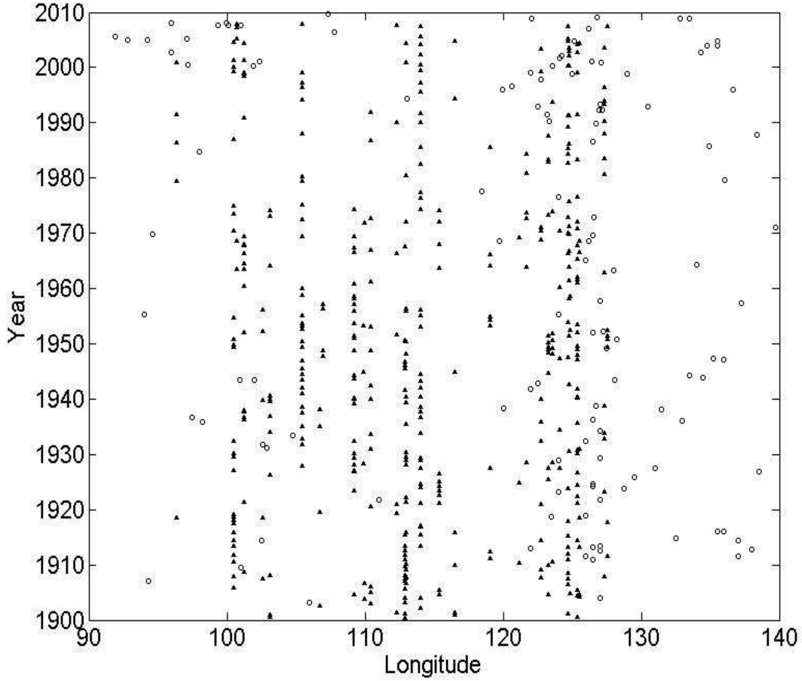


Figure 2. Time and location (longitude) of earthquakes (circles) and eruptions (triangles).

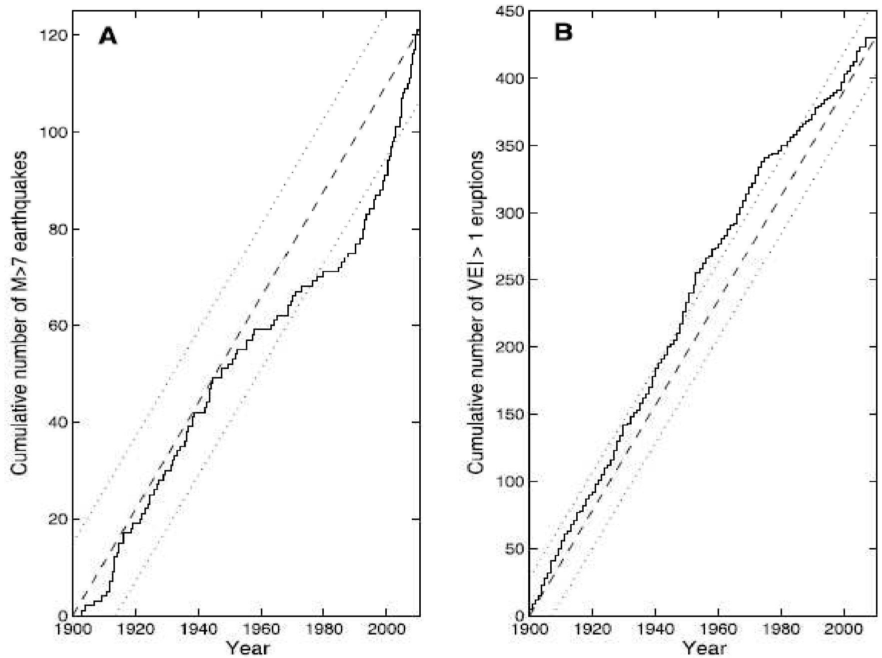


Figure 3. (a) Cumulative numbers of earthquakes with $M \geq 7$ and (b) eruptions with VEI ≥ 2 at volcanoes with at least three eruptions from 1900 to 2010. The dotted lines indicate the 95% Kolmogorov-Smirnov limits.

General Test for Triggering

Marzocchi (2002): Perturbation function:

$$\Phi(\tau) = \frac{1}{M}\sum_{i=1}^{M}\left[\sum_{j=1}^{N} M_{0_j}\,\omega(d_{ij})\mathrm{H}_i(\tau; T_i - t_j)\right]$$

Measures average stacked (over time) perturbations on volcanoes (i), by earthquakes (j) in previous time window τ

Significance assessed by randomization test:

VEI of the Data Set	τ (years)	P Value
2+	0.002	0.11
2+	10	0.80
3+	0.002	0.02
3+	10	0.31
4+	0.002	0.18
4+	10	0.11

No clear evidence of any overall effect. What about individual volcanoes?

Point Process Theory

- Point process conditional intensity $\lambda(t)$:
  - depends on the history of the (e/q-volcano) system up to time t
  - probability of an eruption in a small time interval $(t,t+\Delta)$ is $\sim\lambda(t)\,\Delta$
  - given events at t_n : $0 < t_1 < t_2 < \ldots < t_N < T$, the log likelihood is

$$\log L = \sum_{n=1}^{N} \log \lambda(t_n) - \int_0^T \lambda(t)\,dt$$

This weighs both positive and negative evidence

Baseline stochastic models

Last eruption: volume v, at time u

- Poisson process (PP), $\lambda(t) = \lambda_0$

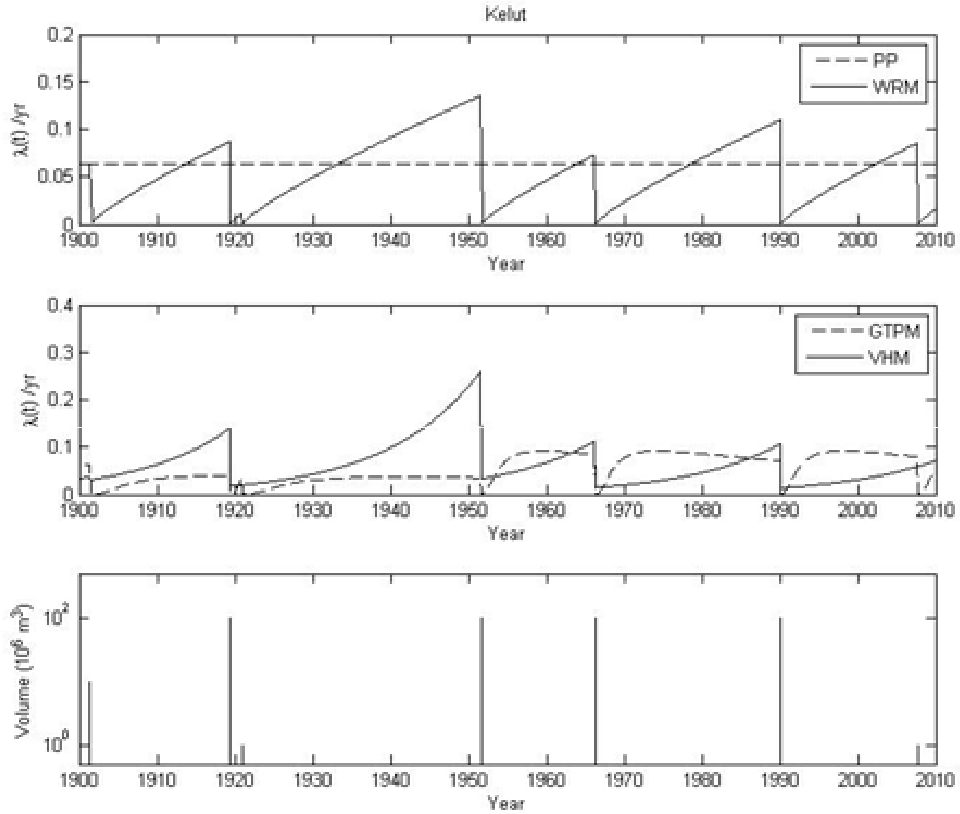
- Weibull renewal model (WRM),

$$\lambda(t-u) = \alpha\beta^{\alpha}(t-u)^{\alpha-1}$$

- Generalized time predictable model (GTPM)

$$\lambda(t-u|v) = \frac{\frac{1}{(t-u)\sigma\sqrt{2\pi}}\exp\left\{-0.5\left[\frac{\log(t-u)-\alpha-\beta v}{\sigma}\right]^2\right\}}{1-\Phi\left[\frac{\log(t-u)-\alpha-\beta v}{\sigma}\right]}$$

(Marzocchi and Zaccarelli, 2006)



- Volume History Model (VHM)

$\lambda(t) = \exp\{\alpha + \nu[\rho t - V(t)]\}$, where V(t) is the cumulative volume erupted prior to time t (Bebbington, 2008)

Incorporating E/Q Triggering

Multiply baseline point process intensity by a triggering term:

$$\lambda_i(t) = \lambda_i^{(B)}(t)\lambda_i^{(T)}(t)$$
$$= \lambda_i^{(B)}(t)\left\{1 + \sum_{j:s_j<t} \exp\left[-a(t-s_j) - b\log r_{ij} + cm_j\right]\right\}$$

where the jth earthquake occurs at time s_j , j =1,...,J, a distance r_{ij} from volcano i, and has magnitude m_j

- Model without triggering nested
- Triggering decays exponentially with time
- Triggering decays with distance as a power law
  (static stress ~r^{-3} , dynamic stress ~$r^{-1.66}$)
- Exponential increase with magnitude commensurate with increase in action radius proportional to rupture length (Lemarchand and Grasso, 2007)

Best Model (by AIC)

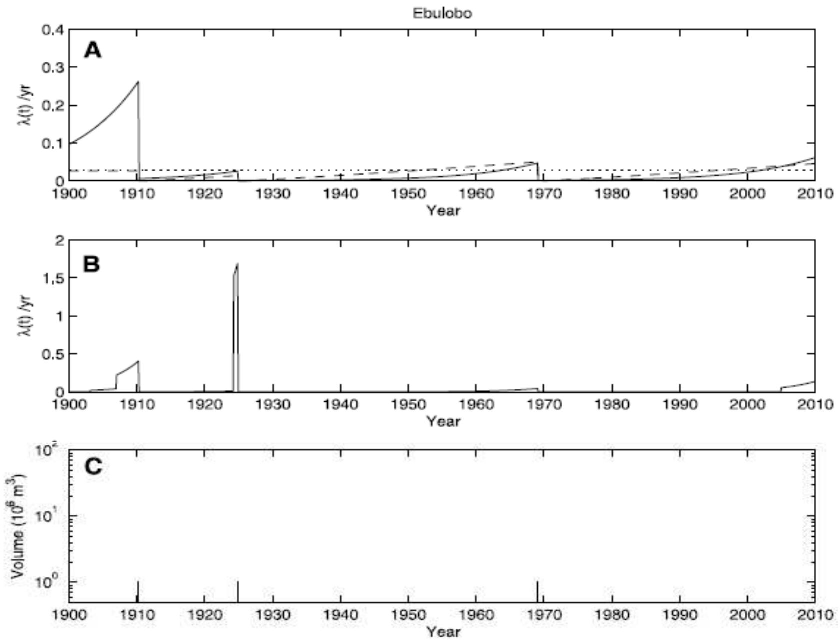


Figure 9. Ebulobo volcano. (a) Fitted conditional intensities (nontriggered): Poisson (dotted), Weibull renewal (dashed), and volume history (solid). (b) Fitted conditional intensity for the triggered volume history model (note difference in vertical scale from Figure 9a); the timing of relevant earthquakes are indicated by upward jumps. (c) Time size (VEI) plot of eruptions.

'Best' model independent of number of eruptions, location of volcano

Model	No. Parameters	No. Volcanoes
Poisson	1	10
Weibull Renewal	2	4
GTPM	3	4
Volume History	3	10
Poisson w. E/Q triggering	4	0
Weibull Renewal w. E/Q triggering	5	0
Volume History w. E/Q triggering	6	7

Are the 7 (out of 35) 'triggered' volcanoes due to more than random chance?

- As our models are nested, we can use a likelihood ratio test.

Improvement relative to Poisson process

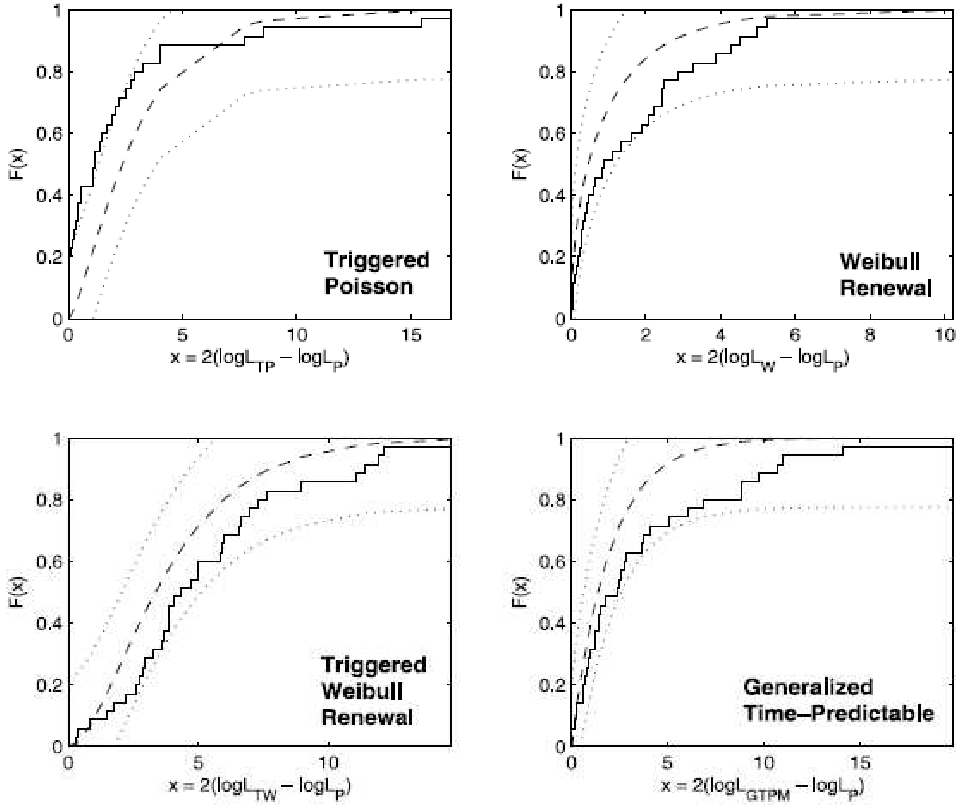


Figure 4. AIC improvement relative to the Poisson process. The solid line is the empirical (35 volcanoes) distribution of $\Delta\mathrm{AIC} + 2(k-1)$, where k is the number of parameters in the given model and $\Delta\mathrm{AIC}$ is the difference in AIC from the Poisson process. The theoretical χ^2_{k-1} distribution is the dashed line, and the dotted lines are the 95% Kolmogorov-Smirnov limits.

Volume dependence and triggering

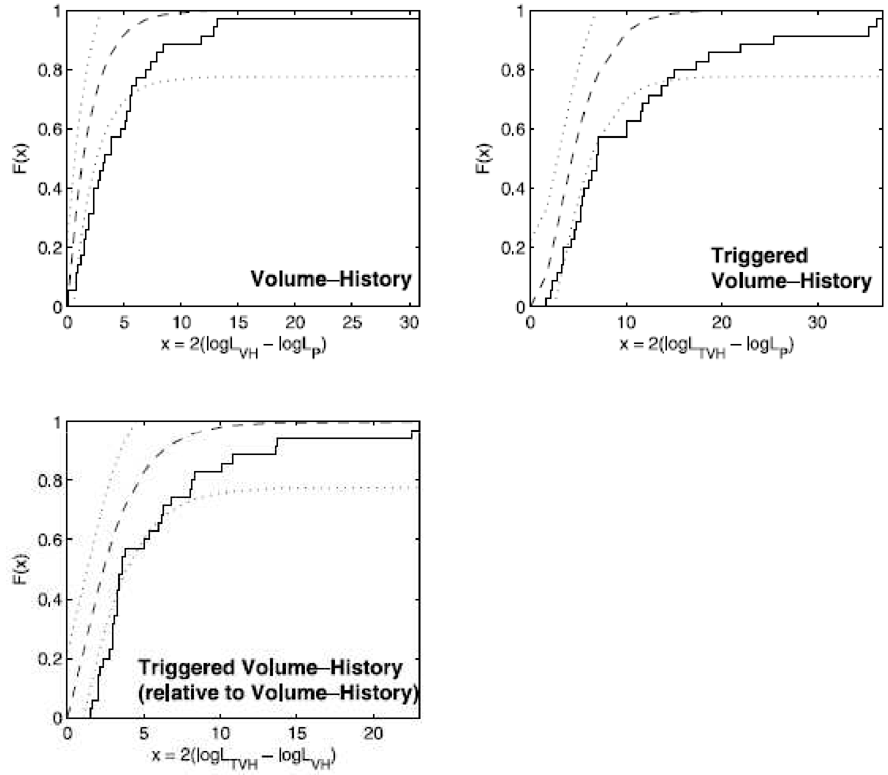


Figure 5. (top) AIC improvement relative to the Poisson process. The solid line is the empirical (35 volcanoes) distribution of Δ AIC + $2(k-1)$, where k is the number of parameters in the given model and ΔAIC is the difference in AIC from the Poisson process. The theoretical χ^2_{k-1} distribution is the dashed line, and the dotted lines are the 95% Kolmogorov-Smirnov limits. (bottom) The same for the triggered volume history model relative to the volume history model.

Volume dependence and triggering – Individual Volcanoes

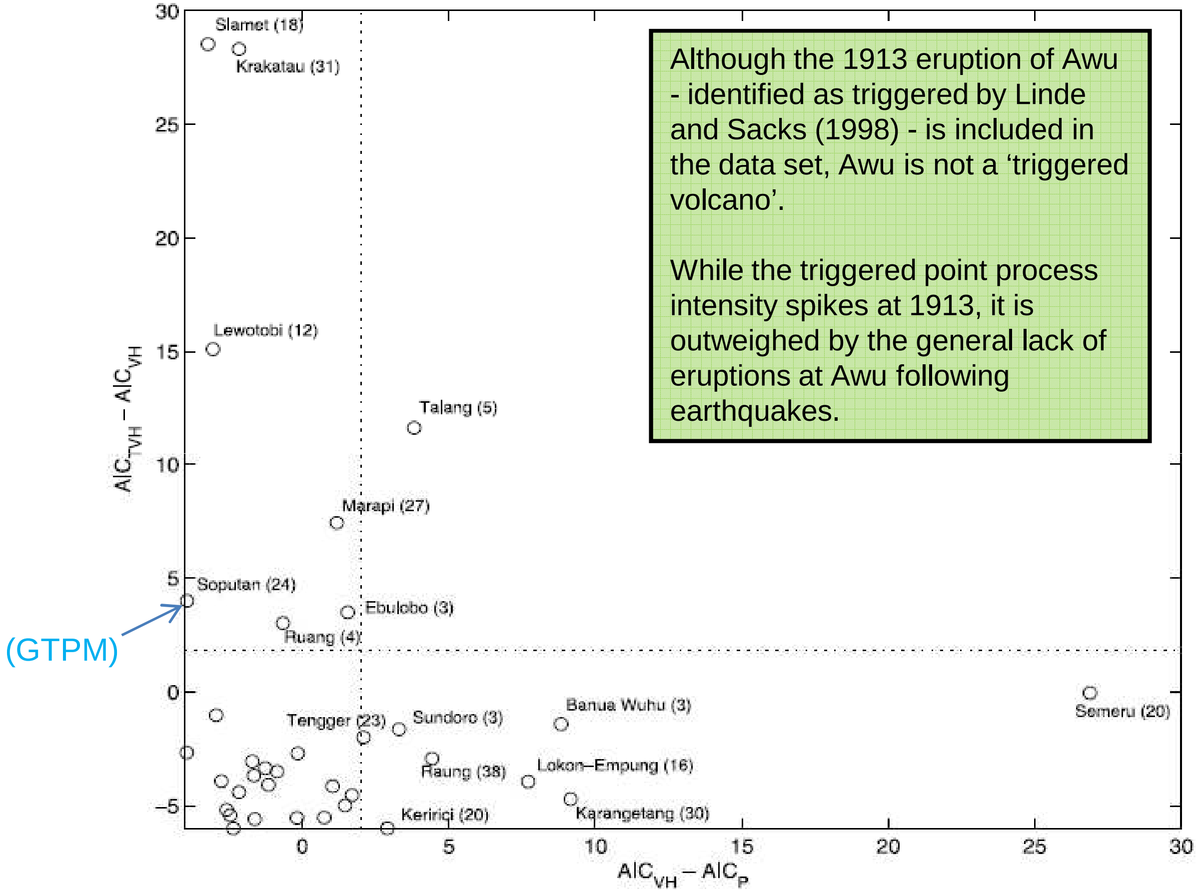


Figure 6. AIC improvement from incorporating volume history and then earthquake triggering. The dotted lines indicate the 5% level of significance. The number of eruptions follows the volcano name.

Although the 1913 eruption of Awu - identified as triggered by Linde and Sacks (1998) - is included in the data set, Awu is not a 'triggered volcano'.

While the triggered point process intensity spikes at 1913, it is outweighed by the general lack of eruptions at Awu following earthquakes.

- While approximately 0.3–0.4% of eruptions are directly triggered (Linde and Sacks 1998), here 25% occur at volcanoes with a statistically significant tendency to triggering.
- With the exception of Ruang, all the triggered volcanoes possess multiple vents.

Triggering Decay

Remember that our basic unit of investigation is a volcano, not an eruption.

Time decay (a):

- 1 ‘instantaneous’ (Lewotobi) ~ Linde and Sacks (1998) idea of triggering
- 2 time independent (Ebulobo, Ruang) - magma system constantly in/near criticality?
- 4 slowly decaying, with half-lives from 2 (Talang) to 18 (Marapi) years

  ~ Walter and Amelung (2007), Watt et al (2009) triggering

Table 3. Estimated Triggering Parameters in Model (12) for Volcanoes With Triggering

	Triggering Parameters		
Volcano Name	a (/yr)	b (/km)	c
Marapi	0.039	0.002	0.871
Talang	0.351	8.20	6.56
Krakatau	0.065	1.22	0.856
Slamet	0.055	0.669	0.254
Ebulobo	10^{-21}	1.72	26.2
Lewotobi	6.90	0.646	0.724
Ruang	10^{-11}	11.2	21.7

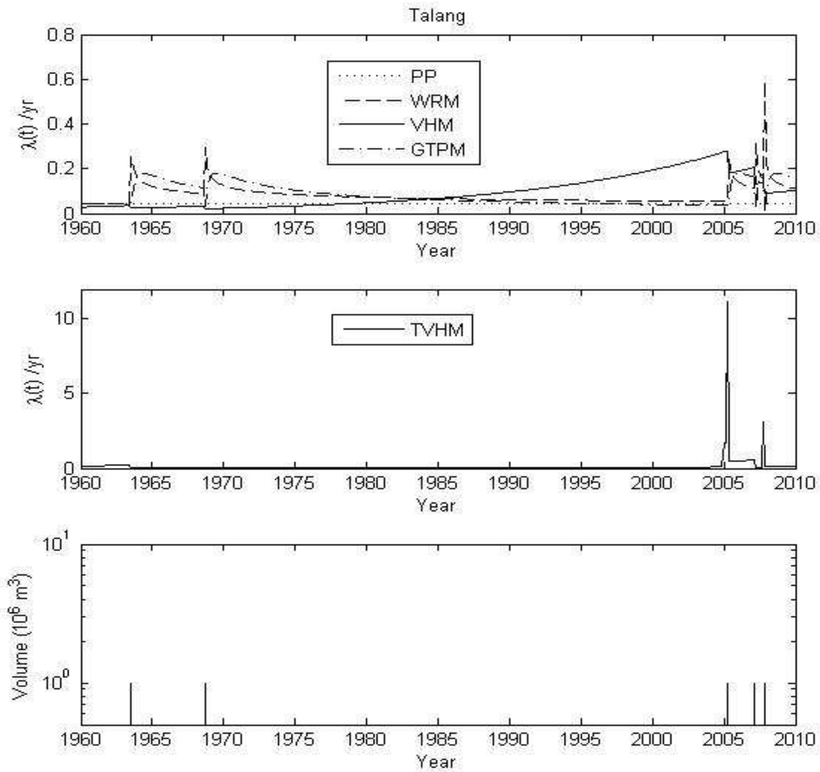
Distance decay (b):

- 1 far field (Marapi) ~ Linde and Sacks (2002)
- 2 very local (Talang, Ruang)
- 4 consistent with previous results for M=7-7.9 E/Qs
  - Decay slower than expected for dynamic/static stress.

➢ Major role being played by viscoelastic relaxation, or tectonic coupling between earthquakes and eruptions?

Interpretation of Triggering – Clock Advance

- In order for triggering to be recognized, we must account for the erupted-volume history of the volcano.



- Size of eruption appears to be independent of whether it was triggered.

- The 2005 eruption of Talang has a spike derived from the 2004 Sumatra earthquake (cf. Walter and Amelung, 2007), as do subsequent eruptions - from the M>7 aftershocks.

- We conclude that triggering affects volcanoes that were ‘ready’ to erupt – a form of ‘clock advance’ familiar in the earthquake literature.

References

- Barrientos SE (1994) Large thrust earthquakes and volcanic eruptions, Pure Appl Geophys 142, 225-237
- Bebbington MS (2008) Incorporating the eruptive history in a stochastic model for volcanic eruptions, J Volcanol Geotherm Res 175, 325-333
- Bebbington MS, Lai CD (1996) On nonhomogeneous models for volcanic eruptions, Math Geol 28, 585-600
- Lemarchand N, Grasso J-R (2007) Interactions between earthquakes and volcanic activity, Geophys Res Lett 34, L24303
- Linde AT, Sacks IS (1998) Triggering of volcanic eruptions, Nature 395, 888-890
- Marzocchi M (2002) Remote seismic influence on large explosive eruptions, J Geophys Res 107, 2018
- Marzocchi W, Zaccarelli L (2006) A quantitative model for the time-size distribution of eruptions, J Geophys Res 111, B04204
- Marzocchi W, Casarotti E, Piersanti A (2002) Modeling the stress variations induced by great earthquakes on the largest volcanic eruptions of the 20th century, J Geophys Res 107, 2320
- Walter TR, Amelung F (2007) Volcanic eruptions following M≥9 megathrust earthquakes: Implications for the Sumatra-Andaman volcanoes, Geology 35, 539-542
- Watt SFL, Pyle DM, Mather TA (2009) The influence of great earthquakes on volcanic eruption rate along the Chilean subduction zone, Earth Planet Sci Lett 277, 399-407