Scale dependence in earthquake processes and seismogenic structures

Keiiti Aki

Department of Earth Sciences, University of Southern California, and Observatoire Volcanologique du Piton de la Fournaise, Institut de Physique du Globe de Paris (e-mail: aki@iremia.univ-reunion.fr; phone: 262-275-292; fax: 262-591-204).

Abstract

If earthquakes are self-similar fractal processes with no scale-dependence, their deterministic modeling will require an infinite number of model parameters. The existence of the seismic guided waves trapped in a fault zone clearly demonstrates a scale-dependent departure from the self-similarity, and offers possibilities for a deterministic modeling of earthquakes with a finite number of parameters. This paper discusses recent results on the scale-dependence of earthquake processes and seismogenic structures in relation to their deterministic modeling.

Introduction

If we want to predict a natural phenomenon by modeling it deterministically, the number of model parameters must be manageable. Since an infinite number of parameters are needed to define a scale-independent self-similar process deterministically, in order to define a system of manageable number of parameters for an earthquake process, we need to recognize its scale dependence.

We start with modeling individual earthquake faults and review their parameters estimated from geological and seismological observations with a particular reference to the stability condition proposed recently by Madariaga et al. (1998, BSSA).

Seismological and geological observations also suggest that the scale length of heterogeneities on earthquake faults may be restricted between the fault-zone thickness (a few hundred meters in California) and the thickness of the brittle zone (around 15 km in California). Recent observations on the frequency dependence of seismic attenuation by Adams and Abercrombie (1998, JGR) show anomalously high attenuation for seismically active regions between about 0.1 and 10 Hz, which may correspond to the above range of the fault zone heterogeneity.

The two orders of magnitude in the heterogeneity scale length, however, is still very large, and a deterministic modeling of such structures and processes in a region of several hundred kilometers size requires hopelessly many model parameters. In comparison with earthquakes, active volcanoes may be simpler in terms of parameters needed for describing the system. Since there is a basic similarity between the two phenomena that the mass/energy supplied constantly (from plate motion for earthquakes, and supply of melt from the upper mantle for volcanoes) is divided into episodes (earthquakes of various sizes, and eruptions of various modes), lessons learned in a deterministic modeling of an active volcano may shed some light for a promising direction of modeling earthquakes for prediction.

Model parameters of earthquake rupture propagation

Recently, Madariaga et al. (1998, BSSA) made a finite difference simulation of a spontaneous propagation of rupture with the slip-weakening and rate-dependent friction law, and found that for a stable simulation, the characteristic weakening slip must be greater than 4 times the slip unit defined by the yield stress and the grid interval which is taken to be the thickness of the fault zone. Using the fault zone parameters estimated from geological and seismological observations, we shall discuss what this condition means for actual earthquakes.

Observations on the fault slip and on the fault-zone trapped waves along the fault of the Landers earthquake of 1992 demonstrated that the fault segmentation observed on the surface persists to the bottom of the brittle zone, and that the thickness of the fault zone is about 180 meters. These observations fit well with the specific barrier model of Papageorgiou and Aki (1983) who found a simple systematic relation among earthquake magnitude and model parameters determined for major California earthquakes. The result from the Landers earthquake not only confirm the basic assumptions underlying the barrier model, but fits well with the systematic relation obtained earlier.

According to the above systematic relation, the logarithm of the barrier interval increases linearly with the magnitude, from about 2 km for M=6 to about 20 km at M=8. On the other hand, the fault zone thickness estimated from fmax is roughly independent of the magnitude. The fault zone thickness estimated from the trapped mode also shows this magnitude independence; 160 m for the Parkfield segment and 180 m for the Landers earthquake fault (Li et al, 1990. 1994, 1997, and 1998).

Following the model of Papageorgiou and Aki (1983) but replacing the estimate of fault zone thickness from fmax by that from the trapped mode, we can revise the estimate of cohesive stress (yield stress), characteristic weakening slip, and other parameters of the slip weakening fault model. These results show that the condition of Madariaga et al.(1998) mentioned above is not met if the fault zone thickness is taken to be the grid distance. The thickness must be 4 to 6 times the grid interval to simulate these California earthquakes. I am not aware of any simulation studies for such a thick fault zone.

Frequency-dependent seismic attenuation in seismically active regions

The results obtained by applications of the specific barrier model to major California earthquakes suggest a range of heterogeneity scale lengths (barrier intervals) along the faults, between a few hundred meters and 15 km or so. The lower limit corresponds to the fault zone thickness, and the upper limit corresponds to the thickness of the brittle zone. The existence of such a lower limit has been indicated by a variety of observations, including (1) the source controlled fmax effect for large earthquakes,

(2) constant corner frequency independent of magnitude for small earthquakes, (3) a kink in the magnitude-frequency relation, and (3) the existence of an upper fractal limit in the fault trace geometry.

An additional support to the above range of fault zone heterogeneity scale lengths may be found in a recent paper by Adams and Abercrombie (1998) who studied the attenuation of S waves in the frequency range up to 100 Hz using deep borehole data. They found that Q^{-1} shows a broad peak between 0.1 and 10 Hz for seismically active regions which may corresponds to the scatterers/absorbers size of several hundred meters to several tens of kilometers.

Modeling of an active volcano for prediction

The above range of the heterogeneity scale lengths needed for a deterministic modeling of a seismic region with a linear dimension of several hundred kilometers is discouraging. It appears to me that the problem is too big to be solved in a near future. For this reason, I decided to work on the prediction of volcanic eruptions. A volcano is a more isolated system than a system of faults. The fractal behavior seems to be weaker, and the number of system parameters can be much smaller. The current model I am working on, consists of 3 reservoirs and 7 channels connecting among reservoirs, the upper mantle and the surface. The number of parameters of the current model is 36, and the model is intended to simulate 52 eruptions occurred since 1930 at Piton de la Fournaise, an oceanic island volcano in the Indian ocean. Hopefully lessons learned by working with eruptions may help to find promising directions for the earthquake modeling for prediction.