Relative quiescence reported before the occurrence of the largest aftershock (M5.8) with likely scenarios of precursory slips considered for the stress-shadow covering the aftershock area

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Abstract: Monitoring of aftershock sequences to detect lowering activity, relative to the modeled rate (the relative quiescence), becomes realistic and practical in predicting the enhancement of the likelihood of having a substantially large aftershock, or even another earthquake of similar size or larger. A significant relative quiescence in the aftershock sequence of the 2005 March earthquake of M7.0 off the western coast of Fukuoka, Japan, was reported two weeks before the largest aftershock of M5.8 that also hit the Kyushu District. The relative quiescence was discussed in relation to the stress-shadowing as inhibiting the activity due to probable precursory slips, which are retrospectively speculated in more detail.

1. Introduction

On 20th March 2005, a strong earthquake of M7.0 took place off the coast of western Fukuoka Prefecture, Kyushu District [cf., Figure 1]. The probability forecast of the occurrence of M\geq5.5 aftershocks, announced on March 21st by the Japan Meteorological Agency (JMA), was less than 10\% for the next three days period, with a much less probability for a further few months period. In fact, the largest aftershock of M5.8 occurred one month later, which would suggest the failure of the forecast.

On the other hand, the statistical result from Japanese data [\textit{Ogata}, 2001] suggests that the probability of having another large earthquake of a similar size to the mainshock becomes several times greater than such a normal probability, if the aftershock activity of the first event shows anomalous decay. Therefore, we need to pay careful attention to anomalous activity in the sequence.

For predicting large aftershocks, \textit{Matsu'ura} [1986] noted the utility of the quiescence in aftershock occurrences relative to the Omori-Utsu decay [\textit{Omori}, 1894; \textit{Utsu}, 1961]. \textit{Ogata} [1988, 1992, 2001] studied the quiescence relative to the epidemic-type aftershock sequence model (ETAS model), which is a natural extension of the Omori-Utsu model, useful for the detailed description of aftershock sequences as well as general seismicity: the reader is referred to \textit{Ogata} [1992, 1999, 2001, 2005a, b, c] and \textit{Utsu and Ogata} [1997] for the statistical method using the ETAS model, including the significance test of the change of seismicity pattern. Then, using the model, some retrospective case studies [\textit{Ogata et al.}, 2003; \textit{Ogata}, 2005a, b] are concerned with the phenomenon that the stress-shadow [e.g., \textit{Harris}, 1998] inhibits normal decay of aftershock activity.
2. The relative quiescence and speculations based on the stress-shadowing

Here I represent a monitoring experiment to detect the aftershock anomaly of the March 20th earthquake of M7.0 in Kyushu District, Japan. At the meeting of the Coordinating Committee for Earthquake Prediction, Japan, held two weeks after the mainshock, I reported the significantly lower activity of the aftershock occurrence than the predicted one by the ETAS model (relative quiescence) [Ogata, 2005c]. This was the result based on the data for the period up until 5th April (vertical solid lines in the Figure 2 in the right side).

Furthermore, in order to predict likely location of a large aftershock or another proximate large earthquake, it is assumed that a significant slip may occur within and near to the source of the suspected earthquake due to the acceleration of quasi-static (slow) slips on the fault as the time of rupture of the major asperity approaches. For example, such a procedure is indicated by the analysis of small repeating earthquake data [Uchida et al., 2004]. Such a scenario for the prediction can be useful for explaining the anomalous features. Thus, we should look carefully at the activity in the stress-shadow [Ogata, 2005a-d], to explain it as transferred from the slip.

Nevertheless, in fact, given an anomaly of seismicity rate change, the difficulty lies in identifying the slip location and its imminence to a major rupture. Most of them are usually unknown unless any other data or constraints, such as geodetic ones, are available. Even if it is identified, it may be in an area of the habitual slipping or intermittent creeping. Thus, in order to make a probability forecast of a likely large earthquake, we need to make and examine all possible scenarios based on the available knowledge in seismology, tectonics etc. Actually, for probable predictions, Ogata [2005c] explored and reported several scenarios of some thinkable slow slips that could have been triggered by the main M7.0 rupture, and moreover that such a slip, in turn, transferred the stress-shadows covering the majority of the aftershock volume. Such a slip could have occurred within a conjugate fault of the main rupture fault, or several known active faults near the rupture fault. For example, however, it has not been likely occurred within the Kego Fault (cf., Figure 1) that runs through the urban area in the city of Fukuoka, since it must result in a stress-increase in the entire aftershock region; namely, no part of aftershock volume can be the stress-shadow.

One month after the mainshock, on April 20th, the largest aftershock of M5.8 took place in the south-western extension of the main aftershock volume, but the strike angle of the rupture fault is significantly different from the main fault. The hypocenters and depths against time plots of the aftershocks indicate the secondary aftershocks following the largest aftershock, which reveals outline of the ruptured fault of M5.8 (the area with densely populated black circles around 130.3°E). In fact, the above mentioned report failed to predict this rupture fault, but the scenario itself appears to be still valid. Based on the hypocenter distribution, we may have the following explanation for the observed relative quiescence in the aftershock activity.
Assuming that there is a precursory slip on the strike-slip fault surface (the area covering the seismicity gap between the main aftershock volume and the secondary aftershock volume), Coulomb failure stress-changes are calculated at a depth of 5km and 10km, where $\Delta CFS = \Delta(\text{shear-stress}) - \mu' \Delta(\text{normal-stress})$ with the apparent friction coefficient $\mu' = 0.4$ being assumed, and positive normal stress means the compression. The $\Delta CFS$ values indicate that the stress increased in the shallower eastern part of the aftershock volume, while the aftershock volume was mostly in the stress-shadow for the deeper part, especially the shadowing is strong in the eastern part of the aftershock volume. These features are consistent with the fact that the aftershocks migrated from the deep to the shallow in the eastern region, whereas the migration is not seen in the western region.

Likewise, the same speculated slip should transfer the stress-shadow covering the active off-fault clusters in the depth range 6 ~ 8.5km beneath Hakata Bay, the activity of which was triggered by the main rupture with a half day’s delay. The shadowing due to the preslip before the largest aftershock then seems to cause a lowering in the seismicity about 2 weeks prior to the occurrence of the largest aftershock. Here one may argue that the lowering may be understood as seismicity rate-change of Dieterich [1994, Figures 2 and 5] that represent a transition from stable rate increase and delayed decay off the fault source. However, although the rate decays gradually after mid-May, it appears that the focal turning point decrease is too drastic for the characteristic time of natural transition to the delayed decay. Indeed, the rate jumped down, reducing to 20% of the previous rate as seen from the slopes of the cumulative function for the period before the largest aftershock.

The similar stress-shadowing scenario can also be well applied to the relative quiescence in the secondary aftershock sequence following the largest aftershock of M5.8 before the M5.0 event that occurred on 2nd May 2005 [Ogata, 2005c].

3. Concluding Remarks

Since aftershocks are triggered by complex mechanisms under fractal random media, their interactions are too complicated to calculate the stress-changes within and near to the field. Thus, the ETAS model based on the empirical laws of aftershocks has been used as a practical representation of locally triggered (self-exciting) seismicity. Then, the diagnostic analysis based on fitting the ETAS model is helpful in detecting exogenous stress-changes. Indeed, these changes can be so slight compared to the self-exciting changes that even current state of the art methods and the geodetic records from the GPS network can barely recognize systematic anomalies in the time series of displacement records.

The main results in the present manuscript do not agree with the claim that there should be a threshold value of $\Delta CFS$ capable of affecting seismic changes. Although the stress-decrease due to precursory
slips can be small in the order of a few tens of millibars or less, the number of occurred and potential earthquakes of moderate or small sizes in a receiver region can be large enough to make a statistically significant detection of the relative quiescence. The scenarios of the relative quiescence rely on the seismicity rate change based on the rate-and-state friction law [Dieterich, 1994] as the quantitative basis of the triggering [Toda and Stein, 2003; Ogata, 2004]. The readers are referred to Ogata [2005d] for some reasons of empirical facts that the relative activation is not very sensitive compared to the relative quiescence.

In summary, the present manuscript supports the idea that aftershock activity is sensitive enough to a slight Coulomb stress-decrease, depending on the degree of homogeneity of aftershock fault mechanisms, caused by a small slip elsewhere. Thus it will be useful to make careful monitoring of the aftershock activity using the ETAS model to detect the relative quiescence, to identify the stress-shadow areas, and eventually to consider likelihood of preslips in the suspected nearby faults.

**References**


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