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Rupture imaging of the Wenchuan earthquake and advice for Chinese earthquake early warning system

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ABSTRACT :

Using the teleseismic body waves recorded by Hi-net array, the rupture image of the 2008 Wenchuan earthquake is studied by the back-projecting method. Our results show that seismic energy is mainly released in the area north to the hypocenter. Comparing with historical seismicity, aftershock rate in the source area is significantly active with a characteristic time of 11 years, indicating that seismicity in this area in the future ten years is significantly higher than background earthquake rate. A reliably and accurate EEW system is expected to play a central role in helping to mitigate seismic hazard. On the basis of experience from Japanese EEW, we recommend that China should introduce an instrumentally observable intensity scale, deploy intensity seismometers and broadcast the instrumentally observed intensity data to the public. We would point out that prediction of shaking intensity is much more important than estimating the final magnitude. It follows that seismologists should find an effective method to issue the coming S-wave shaking intensity using the P-wave data, and that the public should pay attention to the intensity index, rather than the magnitude.

KEYWORDS:
Source rupture, back-projecting, earthquakes early warning

1. INTRODUCTION

The June 8, 2008, Wenchuan, Sichuan, earthquake occurred in the Longmen Shan region, an area with very steep topographic gradient as a result of the collision between two tectonics plates, the Indian plate and the Eurasian plate. This collision started since 50 Ma and accounted for the high mountains and widespread seismicity observed in western China. Global Positioning System (GPS) observation shows that the India plate has been moving northward at a rate of about 40 mm/year, subducting beneath central Asia and thus pushing Tibetan plateau eastward. As the eastern margin of the ongoing rising Tibetan plateau, the Longmen Shan mountain range hence overrides the Sichuan basin at a rate of about 4mm/year (Zhang et al., 2004) and accounts for the seismic energy released in the 2008 Wenjiang earthquake.

The Wenchuan great earthquake was well recorded by the High Sensitivity Seismograph Network (Hi-net), Japan, established and under operation in *National Research Institute for Earth Science and Disaster Prevention (NIED)* since the 1995 Hyoko-ken Nanbu (Kobe) earthquake hit the Kobe urban (Okada et al., 2004). Hi-net (Figure 1) originally aimed at catching nationwide activity of small earthquakes beneath Japan Islands, improving understanding of the crust and mantle structure beneath Japan, and supplying helpful information for future earthquake prediction. With the help of Hi-net data, NIED has discovered new geophysical phenomena, deep low-frequency tremors, slow slip events, and repeating earthquakes. On the other hand, as a national institute for disaster prevention, NIED had been developing a Real-time Earthquake Information System (REIS) project since 2001. REIS is expected to enable the organizations and people concerned to take substantial disaster mitigation measures rapidly, such as protecting and mitigating damage to life lines, high-precision processing lines and human lives by transmitting seismic data that are from the nationwide networks. The pioneer research of REIS project effectively developed into a five-year government-funded leading project, research project for the practical use of real-time earthquake information network. This project finally led to the construction of the first nationwide EEW system in the world.

In this paper, using the teleseismic body waves recorded by Hi-net, we first study the rupture image by the back-projecting method. We also discuss the future seismicity level in this area on the basis of historical seismicity and aftershock distribution. Finally, on the basis of experience obtained from Japanese earthquake early warning system, we summarize several questions needed to be solved for constructing a Chinese earthquake early warning system.

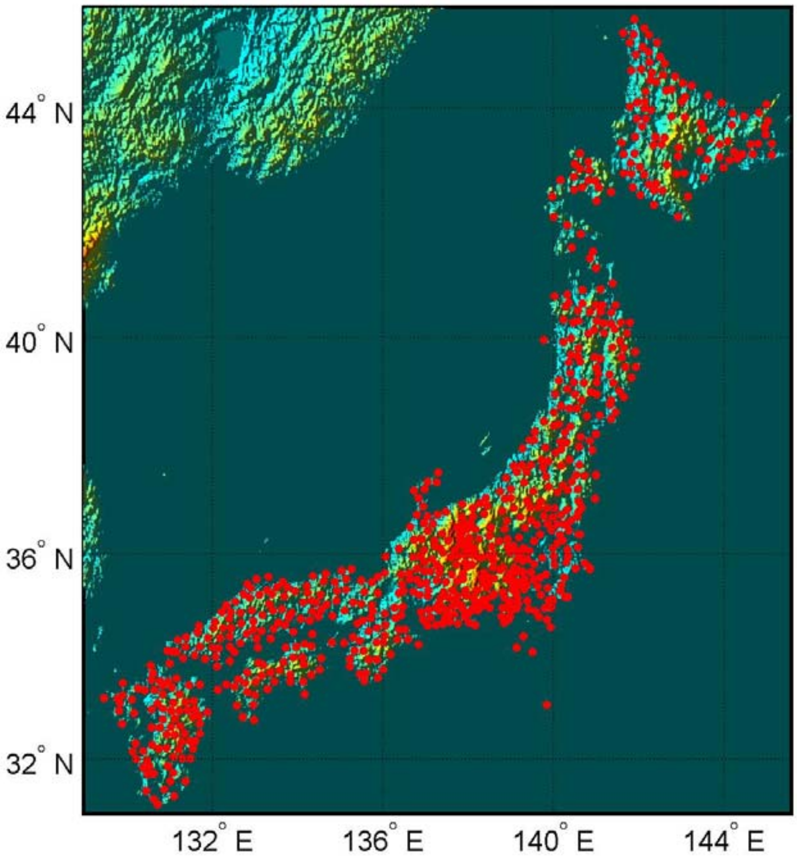

Figure 1 Hi-net station (red solid circles) map.

2. RUPTURE IMAGING

To image the rupture process using teleseismic body wave, here we use the back-projecting method basically similar to that proposed by Ishii et al. (2005, Nature). First, we select the vertical component record at the station with the lowest background-noise as the reference seismogram. We develop a two-step teleseismic P-wave pickup program and apply it to the reference seismogram to automatically detect the P phase arrival. The waveform cross correlation between each seismogram and the reference seismogram is then performed on a 4-s window around the theoretical arrival time calculated by the one-dimensional model IASP91 (*Kennett and Engdahl*, 1991). In this step, seismograms with cross correlation larger than 0.7 are used to obtain a 4-second reference stack. As a correction for the difference between the observation and synthetic travel times, the time shift from the predicted P-wave arrival time is determined by allowing moving the time window ±3s and searching the maximum cross correlation between each seismogram and the reference stack. This step further exclude those with cross correlation less than 0.7. By this criterion 80% of the records are included among the nearly 700 Hi-net records. Finally, we back-project the selected seismograms to the *i*th source grid at source time τ and obtain a stack as written in equation 2.1.

$$U_i^{stack}(\tau) = \sum_n a_n u_n(\tau + t_{ni}^p + \Delta t_n^p) \qquad (2.1)$$

where a_n is the normalizing factor for each seismogram, u_n is the seismogram at the *n*th station, Δt_n^p is the P-wave travel time correction term between the hypocenter and the *n*th station, and t_{ni}^p is the theoretical travel time from the *i*th source grid to station *n*. Instead stacking waveforms corresponding to a fixed time point for each source grid, we stack the seismograms in a time window with duration T (4 sec in this study) and take time-weighted summation of squares of the stacked waveform as an energy release index as in equation 2.2.

$$E_i(\tau) = \sum_{j=0}^{J} w_j U_{stack}^2 (\tau - \tfrac{T}{2} + j/f) \qquad (2.2)$$

where w_j is a weight function, f is the sampling frequency and $J=fT$. Assuming that high-frequency waveform (Hi-net low-cut at 1Hz) mainly comes from direct radiation of the source area, stacking could image the rupture process. Figure 2 plots the maximum energy release for each grid. This figure clearly shows that seismic energy is mainly released in the area north to the hypocenter. In detail, rupture started in the south and smoothly propagated outwards in the first 20 second. From 20 s on, in the area northeast to the hypocenter, a peak energy release with duration of about 20 seconds could be clearly identified. Further northeastwards, a second peak (with the similar duration but much weaker than the first peak) could be found from 60 seconds on. Our results suggest that the rupture properly propagated to the northeast as far as 250km.

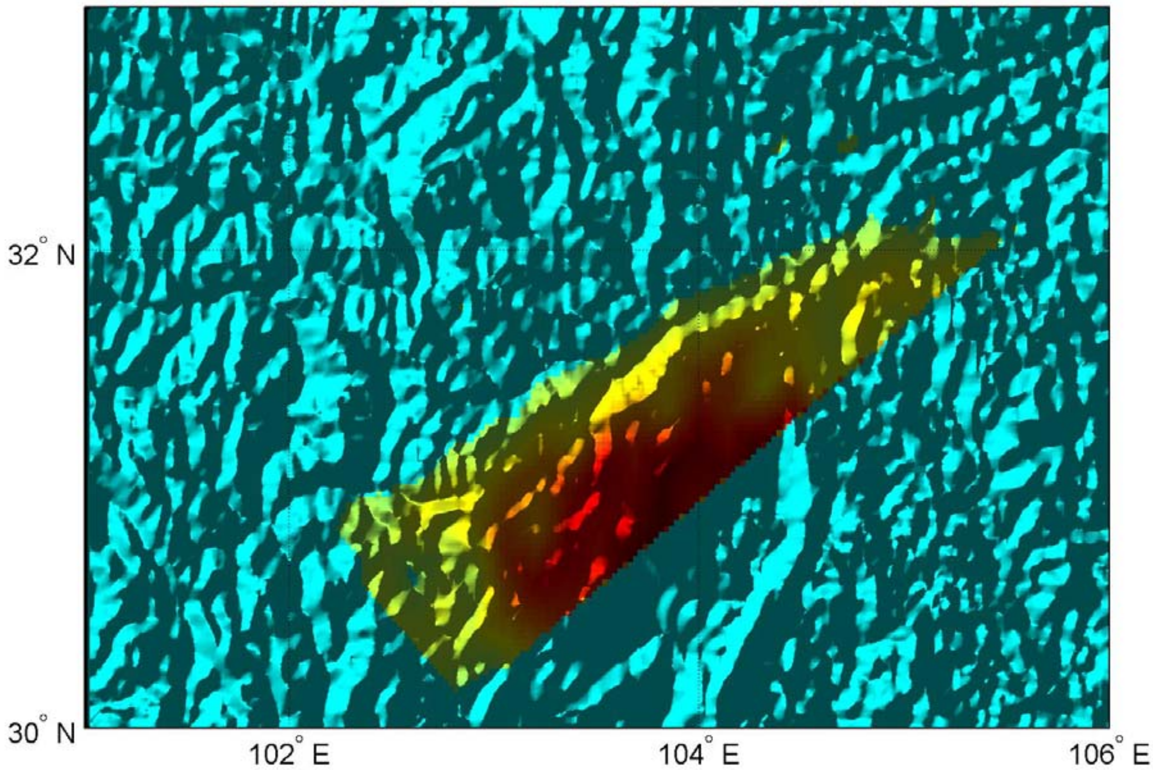

Figure 2 Rupture imaging of the Wenchuan earthquake. Red color means large energy release.

3. AFTERSHOCK ACTIVITY

From Figure 3 and 4 one can compare the background seismicity and aftershock distribution in the Longmen Shan region. Earthquake rate in the source area is relatively low, especially in the north part. Using such a short time window, earthquake hazard in this area might be underestimated. Geological and geomorphic data, however, suggest that faults in Longmen Shan region may move at a rate of at least several millimeters per year and are long enough to sustain a disastrous earthquake (Densmore et al., 2007). Nevertheless, aftershock activity in and around the source area is much higher than the background seismicity. Following the constitutive law for rate of earthquake production, modeling seismicity as a sequence of earthquake nucleation events in which the timing of earthquakes is controlled by stressing history as well as the distribution of initial conditions over the population of nucleation sources (Dieterich, 1994), we can characterize the seismicity rate *R* as equation 3.1

$$R = \frac{r}{a\exp(\frac{-t}{t_a})+1} \quad (3.1)$$

where r is reference seismicity rate, t_a is the characteristic time for seismicity to return to steady rate, and a is determined by the earthquake stress change $\Delta\tau$, the fault constitutive parameter A, and the normal stress σ (equation 3.2).

$$a = \exp(\frac{-\Delta\tau}{A\sigma})-1 \quad (3.2)$$

The reference seismicity rate can be estimated from the background earthquake activity. Using equation 3.1, the characteristic time for the Wenjiang earthquake is estimated as about 11 years, indicating that seismicity in this area in the future ten years is significantly higher than background earthquake rate. Given a reasonable estimate of A=0.005 and hypocenter at 10km depth, stress change due to the main shock could estimated, about 7MPa in this case to explain the observed aftershock activity.

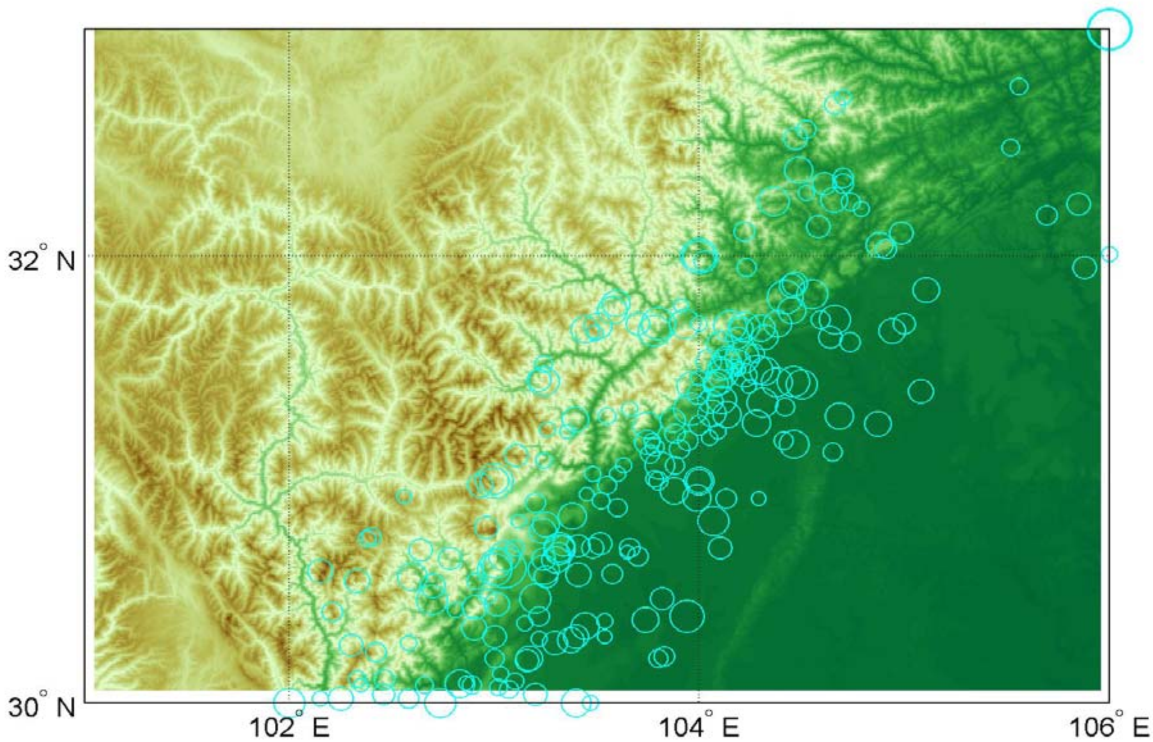

Figure 3 Background seismicity (1960~2008). Blue circles are epicenters and scale with magnitude.

4. EEW AND DISASTER MITIGATION

UREDAS (shaking detector) is one of the earliest EWW systems, which started over 20 years ago for Japanese railways (Nakamura, 1998), but the Hi-net array enables us to develop a nationwide EEW system in Japan (Horiuchi et al., 2005). In 2003, a joint project participated by NIED and the Japan Meteorological Agency (JMA) was started

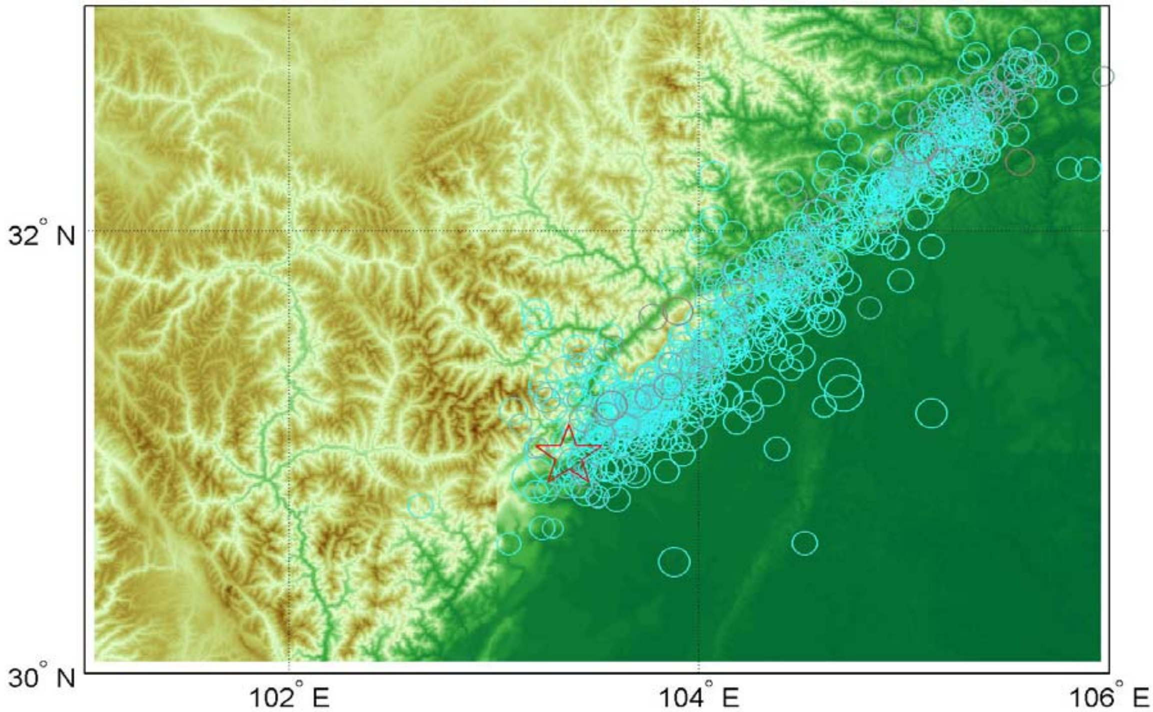

Figure 4 Aftershock distribution map.

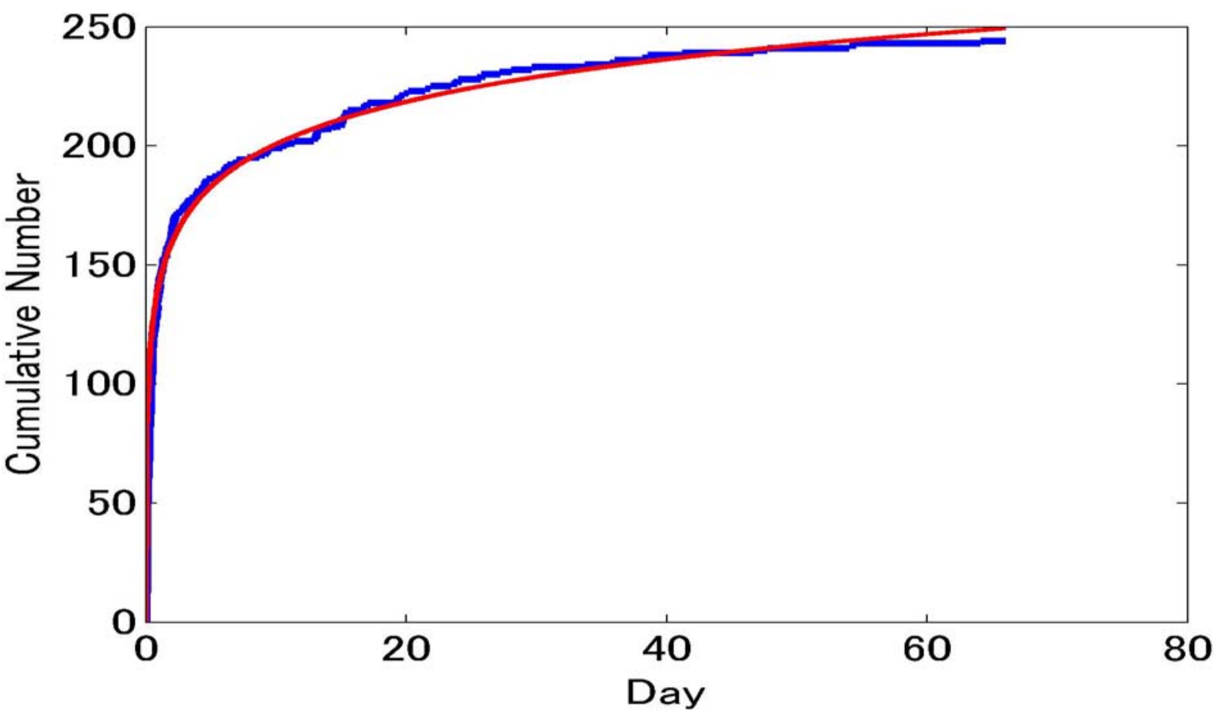

Figure 5 Comparison of observed (blue line) and predicted (red line) cumulative number of aftershock.

in Japan to develop an EEW system. This project aims at: (1) an automatic system to determine hypocenters and magnitudes within several seconds; (2) a database for site amplification effects for shaking intensity prediction; (3) availability of long-term operation and maintenance of the EEW; (4) broadcasting public warning helpful for equipment halting in high vulnerability situations. Including several unsuccessful experiences, the successful early warning issued for the 2008 Iwate Inland earthquake indicates that a reliably and accurate EEW system will play a central role in helping to mitigate seismic hazard. Partly because great Tokai and Tonankai earthquakes are expected to occur in near future, development of a more and more accurate EEW is still undergoing in Japan.

With the rapid economy development, China becomes able to deploy more and more seismic stations. For example, local seismic network planned in Fujian province, southeast of China, is as dense as Japanese Hi-net array. This situation enables local government to operate a local EEW system. Remember that never put all eggs in one basket. Japanese EEW uses different earthquake location methods, including B-Δ single station method (Odaka et al., 2003), the grid search method, as well as the arrival and non-arrival method (Horiuchi et al., 2005). Japanese EEW usually could obtain a reasonable result by using abovementioned different competing methods. Here we would point out some crucial problems needed to be considered.

There are some researches to predict the magnitude of an earthquake using only a couple of seconds of the initial P-wave data (Olson and Allen, 2005; Zollo et al., 2006). However, conventional magnitude is devised to characterize the whole source by seismologists. For an EEW system, we should bear in mind that prediction of shaking intensity is much more important than estimating the final magnitude. It follows that seismologists should find an effective method to issue the coming S-wave shaking intensity using the P-wave data, and that the public should pay attention to the intensity index, rather than the magnitude. Yamamoto et al. (2007) proposed a new magnitude which is estimated from shaking intensity and allows for the rapid and accurate estimate of seismic intensity in an EEW. For example, given measurable seismic intensity, one could calculate real-time intensity using the P-waves, say, I_p like equation 4.1

$$I_p = a\log_{10}(Amp) + b \qquad (4.1)$$

where *Amp* could be a function of maximum amplitude of band-pass filtered velocity or acceleration waveform. In the case of JMA seismic intensity, *a*=2, *b*=0.94 and *Amp* is a value obtained from a time-series that is the vector amplitude of three components of acceleration, which have been band-pass filtered. Since Chinese seismic intensity scale is different from JMA intensity scale, *a* and *b* should be determined such that one can maintain reasonable agreement and continuity between instrumentally observed seismic intensity and historic intensity scale (As a rough estimate, *a* is about 3 and *b* is about 0.6 for Chinese seismic intensity scale). A new scaling parameter can be then introduced as equation 4.2

$$M_I = \frac{I_p}{a} + \log_{10}(r) + \pi f T_p / (2.3Q) + c_p \qquad (4.2)$$

Where, *r, f, T* and *Q* are the hypocentral distance, frequency, travel time, and attenuation Q value. The parameter M_I can be used to predict the seismic intensity in a real-time EEW system as in equation 4.3.

$$I_s = a(M_I - \log_{10}(r) - \pi f T_s / (2.3Q) - c_s) \qquad (4.3)$$

Since JMA intensity is obtained from the band-pass filtered acceleration and acceleration is the second time derivative of displacement, M_I is found to be mainly controlled by the amplitude of short-period seismic waves. It suggests that M_I is a better estimator of seismic intensity in an EEW system than conventional magnitudes. Unfortunately, Japanese EEW adheres to use the conventional magnitude to estimate the seismic intensity, which neglects frequency difference and empirically relates magnitude to seismic intensity. Had JMA adopted the new magnitude proposed by Yamamoto et al., the 2008 Iwate Oki earthquake would probably be warned successful again.

Except in Japan, however, seismic intensity is usually estimated by field survey. An effective EEW system needs both enough academic observation and unbiased public understanding of seismic intensity. Instrumentally measurable, rather than subjective field survey, intensity data or other objectively transformed intensity data are the basis for future prediction. Meanwhile, if the public could not correctly understand what a seismic intensity index means, there is no meaning to issue such a warning. We recommend Chinese government to deploy intensity seismometers and broadcast the instrumentally observed intensity to the public.

Third, we need to tell the public at advance what an EEW system can do and can not do. To prepare for the worst situation, an over-estimation is preferred to underestimation. But too often false warnings would lead to wolf story. The public might not need detailed information, but as for those large factories or plants, warning information should be precise and in time, and false warning should be reduced to the least level. We should take into consider the public acceptability of emergent warning and devise different warning information for difference user.

Finally, we would point out that EEW is not only a seismological system. It can not be short of cooperation from IT, culture, psychological, economical, and administrative organizations. One should never forget to take into account negative effects of EEW information since not all public can correctly understand the EEW information and correctly react. Enhancement of public understanding and training of react to emergent earthquakes is of great important for an effective EEW system.

5. CONCLUSIONS

Using the teleseismic body waves recorded by Hi-net array, we studied the rupture image of the 2008 Wenchuan earthquake by the back-projecting method. Our results show that seismic energy is mainly released in the area north to the hypocenter. Comparing with historical seismicity, aftershock rate in the source area is significantly active with a characteristic time of 11 years, indicating that seismicity in this area in the future ten years is significantly higher than background earthquake rate. A reliably and accurate EEW system is expected to play a central role in helping to mitigate seismic hazard. On the basis of experience from Japanese EEW, we recommend that China should introduce an instrumentally observable intensity scale, deploy intensity seismometers and broadcast the observed intensity data to the public. The new intensity scale should be defined such that one can maintain reasonable agreement and continuity between instrumentally observed seismic intensity and historic intensity scale. We would point out that prediction of shaking intensity is much more important than estimating the final magnitude. If there are sufficient data of seismic intensity, one can introduce a new scaling parameter, which is powerful to predict the seismic intensity from the beginning several second P-waves. It follows that seismologists should find an effective method to issue the coming S-wave shaking intensity using the P-wave data, and that the public should pay attention to the intensity index, rather than the magnitude. EEW should provide different information for different users. Enhancement of public understanding and training of correct react to emergent earthquakes is of great important for an effective EEW system.

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