‘Negative repeating doublets’ in an aftershock sequence

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(Received June 28, 2012; Revised January 13, 2013; Accepted January 28, 2013; Online published September 17, 2013)

We observed some ‘negative repeating doublets’, with nearly opposite three-component waveforms, in the aftershock sequence of the 2008 Wenchuan earthquake. The ‘negative repeaters’ are identified by using the broadband seismic record (with frequency range from 1 to 10 Hz) of the Wenchuan station (WCH) with a near epicenter distance from 19.7 to 26.6 km. These opposite three-component waveforms are not due to the changing of polarities of the seismic station.

Key words: ‘Repeating earthquakes’, waveform cross-correlation, the 2008 Wenchuan earthquake, aftershock sequence.

1. Introduction

In recent years, ‘repeating earthquakes’ in the sense of waveform cross-correlation have been observed over a wide range of magnitudes and diverse tectonic environments such as creeping zones of major faults (Vidale *et al.*, 1994; Rubin, 2002), interplate subduction zones (Igarashi, 2003; Uchida *et al.*, 2010), and inland regions (Schaff and Richards, 2004b, 2011). The properties of ‘repeating earthquakes’, such as the magnitude-recurrence interval scaling, have been utilized to study the physics of earthquakes and faulting; for example, fault healing (Vidale *et al.*, 1994), earthquake source properties (Nadeau and McEvilly, 1997; Rubin *et al.*, 1999; Uchida *et al.*, 2007), slip rate at depth (Nadeau and McEvilly, 1999; Li *et al.*, 2011a, b), temporal variation of deep structure (Poupinet *et al.*, 1984; Zhang *et al.*, 2008), and strength of asperities (Sammis and Rice, 2001). ‘Repeating events’ have also been used to evaluate and improve earthquake location practice (Jiang and Wu, 2006; Schaff and Richards, 2004a; Jiang *et al.*, 2008, 2012) and enhance the capability of detecting foreshocks and aftershocks (Schaff, 2010).

In the sense of waveform cross-correlation, ‘repeating earthquakes’ display nearly identical seismograms at a common station, share the same fault patch, have nearly the same centroid of moment release, and probably have similar focal mechanisms (Rubin, 2002; Schaff and Richards, 2004b). It is somewhat interesting, therefore, that in the ‘repeating aftershocks’ of the 2008 Wenchuan earthquake, there are ‘unusual’ repeating doublets, which have nearly opposite three-component waveforms. This kind of ‘neg-

ative doublets’ have been mentioned by Hauksson and Shearer (2005) when using the HypoDD algorithm to relocate events in Southern California. Schaff (2010) discussed similar cases of the 1999 Xiuyan, China, earthquake sequence, that some portions of the seismograms are similar while others are nearly opposite. Nevertheless, this kind of ‘negative repeating events’ are not common in observations and worthy of special attention.

2. Data Used and Method for Analysis

We used the aftershocks of the 2008 Wenchuan earthquake inside the Longmen Shan fault zone registered in the Monthly Earthquake Catalogue of the China Earthquake Networks Center (CENC), based on observations of the China National Seismograph Network, with M_L ranging from 0 to 5.5. In connection with the Wenchuan Fault Scientific Drilling (WFSD) Project which started in October, 2008, the area chosen for study is the surroundings of the WFSD-1 drilling site, and the earthquake catalogue is selected from 2008/10/01 to 2011/09/15. The magnitude of completeness M_c was estimated to be 1.4 with the Maximum Curvature Method (Wiemer and Wyss, 2000), and, accordingly, altogether 2,631 events at this magnitude and above were selected for study. We used the waveforms of all these events recorded at the Wenchuan station (WCH). Figure 1 shows the velocity response of its vertical component. The waveform data is from the Data Management Center of the China National Seismograph Network, in the SAC format, with a sampling rate of 100 sps.

We read the P and S phase arrivals from the bulletin of the CENC and wrote them to the SAC data. A 1–10 Hz Butterworth band-pass filter was applied to the waveforms. A sliding window was selected starting from the P arrival and extended to 4 times of the $S - P$ travel time difference, covering the whole waveform including the coda (Jiang *et al.*, 2008), with a sliding time -2 s to 2 s and a step of 0.01 s. The cross-correlation coefficient (cc) was calculated by (Båth, 1974)

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Fig. 1. Velocity response (vertical component) of station WCH.

Fig. 2. Background seismicity (from 2008/10/01 to 2011/09/15, gray dots) and the Wenchuan seismic station (WCH, red triangle). Circles highlight the 2,631 aftershocks under study, centered at the WFSD-1 drilling site (red hexagon). The red dot in the left corner stands for the epicenter, or the initiation point, of the 2008 Wenchuan mainshock. The location of the figure is shown in the inset map, highlighting the position of the WFSD-1 drilling site. Blue dots, with light green lines interconnected, show the 150 'repeating doublets' identified by waveform cross-correlation at the WCH station. Red dots, with pink lines interconnected, show the 5 'negative repeating doublets' discussed in this paper.

$$cc = \frac{\sum [f_1(t) - \overline{f_1(t)}] [f_2(t) - \overline{f_2(t)}]}{\sqrt{\sum [f_1(t) - \overline{f_1(t)}]^2} \sqrt{\sum [f_2(t) - \overline{f_2(t)}]^2}}.$$

Unlike traditional processing, which usually uses vertical-component seismograms, we use the three-component waveforms. A threshold of 0.8 was prescribed for the cross-correlation coefficient (cc) to identify the 'repeaters': the case that $\text{abs}(cc)$ of each component of two events is not less than 0.8 is used to select the event pair as a 'repeating doublet'.

3. 'Repeating Events' Identified: Regular 'Repeating Doublets' versus 'Negative Repeating Doublets'

Among the 2,631 events selected for analysis, using the seismic recordings of the WCH station, there were 230 'repeaters' identified, forming 155 'repeating pairs' as shown in Figs. 2 and 4 (note that the case of 'multiplets' makes the number of 'repeating pairs' not simply double the number of 'repeaters'). Remarkably, there are 5 doublets (about 1/30 of the whole event set), with their cc less than -0.8 for all the three-component waveforms. For the Wenchuan station (WCH), the epicenter distances of these 'negative doublets' range from 19.7 to 26.6 km. Figure 3 shows an example of the three-component waveforms of a 'negative

Fig. 3. Filtered three-component waveforms of a 'negative doublet', recorded at the WCH station, and the cross-correlation coefficient (cc). The sliding window starts from the P arrival and lasts four times the $S - P$ travel time difference. The cc values changing with the sliding time (Delta t , from -2 s to 2 s) are shown in the bottom panel, and reach the maximum absolute value at -0.08 s, almost synchronously for the three components.

repeating doublet', with the cc calculated for different sliding windows. Note that the locations in Fig. 2 are from seismological bulletins in which each event is located separately. Accordingly, the length and orientation of the links may be used as a direct indication of the uncertainty in the bulletin location estimates.

One of the causes of the 'apparently negative repeating doublets' may be the variation of the polarities of a seismic station, which has to be excluded in the analysis. To this end, Fig. 4 shows the temporal distribution of the 2,631 aftershocks and the 230 'repeaters' identified at the WCH station. In the figure, horizontal lines linking the two 'repeaters' show the 'repeating pairs', in which regular 'repeating doublets' are shown in blue, while 'negative repeating doublets' are shown in red. From the temporal distribution of the regular 'repeating doublets' and the 'negative repeating doublets', it is unlikely that the 'negative repeating doublets' are caused by the variation of the polarities of the seismic station. Figure 5 shows the cross-correlation coefficients of different 'repeating doublets' with their sequence order. In the figure, blue circles indicate the doublets with positive correlation coefficients, while red dots indicate the 'negative doublets'. Remarkably, there are events which have both 'positive repeater/s' and 'negative repeater/s', as shown by the red circles. This further confirms that polarity change is not likely the cause of the 'negative repeating doublets'.

4. Conclusions and Discussion

In the aftershock sequence of the 2008 Wenchuan earthquake, from 2008/10/01 to 2011/09/15 around the WFS-1 drilling site, and identified by the seismic waveforms (within the frequency range 1–10 Hz) of the WCH station, we observed 5 among 155 'repeating doublets' with almost opposite waveforms for all the three components. Such 'negative repeating doublets' are not likely the result of a polarity change at the seismic station. Clear and simple P -waveforms and S -waveforms at a near-source station are a useful aid in the study of polarity changes. And this is especially clear when considering three-component, rather than single-component, seismograms.

In the identification of 'repeating doublets', a commonly used criterion is that for at least one station, the vertical component seismograms from an 'earthquake pair' have a cross-correlation coefficient (cc) no less than 0.8 (for example, Schaff and Richards, 2004b). Compared with other cases, the WCH station in this study is characterized by its near source distance being less than 30 km. Limited near source stations prevent us from undertaking a detailed investigation of the physical cause of these 'negative doublets' based on the single-station recordings, although the three-component recordings provide more reliable results of cross-correlation. In the single station case, apparently it is not possible to discriminate whether the 'negative doublets' are caused by a 'reversed focal mechanism', that is, the slips

Fig. 4. The 2,631 aftershocks selected (top, in black), and the 230 'repeating events' identified (middle) by the WCH station, with vertical lines showing the magnitude of the events. Horizontal lines (bottom), linking the two 'repeating events', show the 'repeating pairs'. Regular 'repeating doublets' are shown in blue, while 'negative repeating doublets' are shown in red.

Fig. 5. Earthquake doublets recorded at the WCH station. Blue circles indicate the doublets with positive correlation coefficients, while red dots indicate the 'negative doublets'. Red circles show the 2 events which have both 'positive repeater/s' and 'negative repeater/s'. Parameters (as registered in the seismological network bulletins) of these 2 events and their 'positive repeaters' and 'negative repeaters' are:

138	2009-09-25	04:02:25.90	31.33N	103.69E	M 2.7	Event 1
145	2009-10-29	15:18:06.08	31.33N	103.71E	M 1.5	positive partner
151	2009-11-26	16:12:25.20	31.33N	103.71E	M 1.8	negative partner
202	2011-02-03	06:59:37.74	31.30N	103.70E	M 1.7	Event 2
167	2010-02-05	16:15:00.05	31.29N	103.67E	M 2.5	positive partner
205	2011-02-23	21:42:04.62	31.30N	103.66E	M 2.2	negative partner

of the two events are nearly opposite to each other, or they are just caused by a composition of the focal mechanism and the special station-event configuration (referring to figures 4.5 and 4.6 of Aki and Richards, 1980). It is worth noting that the event pair shown in Fig. 3, as well as other pairs which are not shown, are characterized by a large *S*-phase and small *P*-phase, with the *S*-phase being the predominant contributor to the negative cross-correlation coefficient, and the *P*-phase unstable as per positive or negative cross correlation. Classical seismology shows that the case of take-off seismic rays near to the normal direction of the seismic rupture, or along its perpendicular direction, may cause this feature of seismograms (Aki and Richards, 1980). This implies that the 'completely reversed focal mechanism' case cannot be excluded. Whether or not near source recordings are more suitable to identify the 'negative repeaters' is a question to be answered in the future, and whether the 'negative doublets' are a special feature of aftershocks, or are common for all types of earthquake sequences, is another open question at the present time.

Throughout the paper, following previous studies, we have used the wording 'repeating events'. Following convention, we use the word 'repeating' in the sense of waveform cross-correlation. Note that the frequency range, 1–10 Hz, determines the resolution of the 'repeater' identification. That is, 'repeating' events identified by waveform cross-correlation can only constrain the two events within the size of a wavelength (in this case, about 0.5 km), rather than to make sure that the two events are physically 'repeating'. Also, note that the earthquake itself has a limited size of fracture. In this case, it is still too early to discuss whether the 'repeating events', including the 'negative repeating pairs', are located in the same fault patch. As shown in our previous studies (Li *et al.*, 2011b), at the present time what can be done practically, rather than to challenge this limit of resolution, is to reduce the spatial range of the traditional analysis of seismicity to the size of a 'repeating event cluster'. Nevertheless, from the perspective of either the cause of 'repeating earthquakes' or the practical need for identifying 'repeating earthquakes', such 'negative repeating doublets' are worthy of further investigation.

Acknowledgments. Thanks to L. B. Han, C. S. Jiang, H. S. Peng, and W. T. Wang for help and discussion concerning software and data processing, to X. F. Zheng for providing the waveform data, to P. G. Richards for stimulating discussion, and to the anonymous reviewers for constructive comments and valuable suggestions. This work is supported by the WFSO project.

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