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Time-lapse slip variation associated with a medium-size earthquake revealed by “repeating” micro-earthquakes: the 1999 Xiuyan, Liaoning, $M_S = 5.4$ earthquake

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Abstract. We obtained the time-lapse cumulative slip before and after the 29 November 1999, Xiuyan, Liaoning, China, $M_s = 5.4$ earthquake by using “repeating events” defined by waveform cross-correlation. We used the seismic waveform data from the Liaoning Regional Seismograph Network from June 1999 to December 2006. Two “multiplets” located near the seismogenic fault of the 1999 Xiuyan earthquake and the 4 February 1975, Haicheng $M_s = 7.3$ earthquake, respectively, were investigated. For the “multiplet” that occurred before and after the 1999 Xiuyan earthquake, apparent pre-shock accelerating-like slip behavior, clear immediate-post-seismic change, and relaxation-like post-seismic change can be observed. As a comparison, for the “multiplet” near the 1975 Haicheng earthquake which occurred a quarter century ago, the cumulative slip appears linear with a much smaller slip rate.

1 Introduction

Critical-point-like behavior of the preparation process of a single earthquake is a complicated problem with controversial opinions and discussed by many scientists (e.g., Varotsos and Alexopoulos, 1984a, b; Jaumé and Sykes, 1999; Kapiris et al., 2003). The solution has to be multidimensional resulting from the combination of different kinds of precursors with different spatio-temporal scales. For the intermediate-term medium-range scale, the widely-reported and controversial pre-shock accelerating moment release (AMR), or equivalently accelerating slip, mainly focuses on local and/or regional seismicity (e.g., Varnes, 1989; Brehm and Braile, 1998; Jaumé and Sykes, 1999; Robinson, 2000; Bowman and King, 2001; Vere-Jones et al., 2001; King and Bowman, 2003; Robinson et al., 2005; Hardebeck et al., 2008; Mignan and Giovambattista, 2008). For the short-to-imminent-term local scale, foreshock plays an important role (Reasenberg, 1999), causing both the lucky, successful, and controversial prediction of the 4 February 1975, Haicheng earthquake (e.g., Wu et al., 1978; Wyss, 1991; Wang et al., 2006) and the unfortunate and also controversial crisis regarding to the 6 April 2009, L’Aquila (Italy) earthquake (e.g., Papadopoulos et al., 2010; van Stiphout et al., 2010). The present investigation deals with the short-term local scale. Background of the investigation is that, in recent years, “Repeating earthquakes”, identified by cross-correlation of seismic waveforms, have been found to be much more abundant in nature than conventionally expected (Schaff and Richards, 2004a). This provides an innovative tool for imaging the slip rate at depth (Vidale et al., 1994; Nadeau et al., 1995; Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999; Igarashi et al., 2003; Kimura et al., 2006; Li et al., 2007; Rau et al., 2007; Cheng et al., 2007; Li et al., 2009; Schaff, 2010). Up to now, due to limitations on observational conditions, cases of capturing the whole process of pre-, co-, and post-seismic slip evolution by “repeating earthquakes” are still rare. This situation is rapidly changing with the development of seismological observation facilities worldwide. In the present investigation, we cross-correlate the seismic waveforms of the

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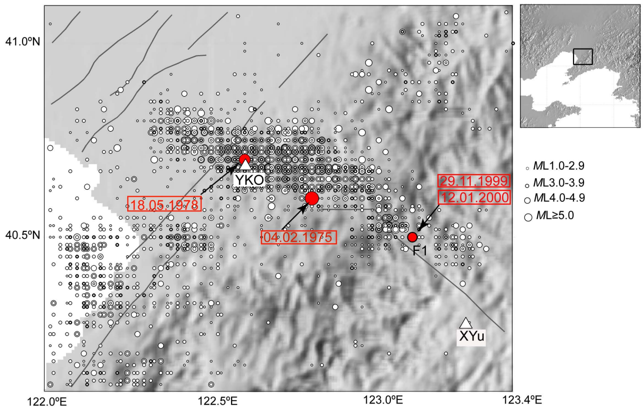

Fig. 1. Earthquakes with $M_L \geq 1.0$ recorded by the Liaoning Province Seismograph Network since 1970. Red dots show the 4 earthquakes with $M_S \geq 5.0$ within this time period, including the 1975 Haicheng $M_S = 7.3$ earthquake, the 1978 Yingkou $M_S = 5.9$ earthquake, the 1999 Xiuyan $M_S = 5.4$ earthquake, and the 2000 Xiuyan $M_S = 5.1$ earthquake. Grid-like distribution of epicenters reflects the limitation of the location capability. For earthquakes larger than $M_S = 7.0$, the epicenter reflects the initiation point of the earthquake rupture. The 1975 Haicheng earthquake ruptured 54 km striking N70° W, with dip angle 81° dipping NE. Tectonic faults are shown by dark gray lines, in which the NW striking fault (F1) is the Haicheng River-Dayang River fault causing the 4 earthquakes above M_S 5.0. Location of the Xiuyan (XYu) station and the Yingkou (YKo) station are also shown in the figure by white triangles.

micro-earthquakes in the region of the 29 November 1999, Xiuyan, Liaoning, China, $M_S = 5.4$ earthquake. This earthquake was one of the important earthquake cases in China, with experimental prediction and detailed follow-up studies (Jiao et al., 2002; Schaff and Richards, 2004b; Schaff, 2010). We explore whether some clues (even if with clearly limited significance caused by the limitation of retrospective case studies) could be obtained by examining the time-lapse slip variation revealed by "repeaters" before and the after this earthquake. This investigation has close relation to, but is intrinsically different from, conventional foreshock studies due to the characteristics of "repeating events".

2 Region under study

The Xiuyan earthquake occurred at 12:10:39 local time (04:10:39 UTC) on 29 November 1999, with the mainshock epicenter located at $40°31.5' \mathrm{N} \times 123°04.5' \mathrm{E}$ according to the report of the Liaoning Province Earthquake Administration. Depth was reported as 10 km, an apparent "convention estimate" due to the limitation on the accuracy and precision of location results mainly caused by the crustal structure model. Routine determination of the Liaoning Province Seismograph Network uses the magnitude transfer relation $M_S = 1.13\ M_L - 1.27$, which gives the surface wave magnitude and the local magnitude $M_S = 5.4$ and $M_L = 5.9$, respectively, for this earthquake in which the directly determined magnitude was M_L using short-period seismic recordings. Field survey, intensity distribution, and aftershock distribution showed that the N64° W nodal of the focal mechanism solution represents the earthquake rupture, dipping NE with dip angle 84°. The earthquake was associated with the left-lateral strike-slip of the northwest-trending Haicheng River-Dayang River fault that also caused the 1975 Haicheng earthquake. At a larger spatial scale, the cause of the active movement of this fault as well as its neighboring faults is still a puzzle in geodynamics, since this region belongs to the margin of the north China craton. The geodynamics for the north China craton to be re-activated is just under study. Figure 1 shows the earthquakes in this region since 1970, together with topography and the distribution of active faults.

3 Data analysis

We used the data from the Liaoning Province Seismograph Network, the former Shenyang Telemetered Seismograph Network, composed of a data center and a central station located in Shenyang (the capital city of Liaoning Province), 15 digital telemetered seismic stations, and 4 data transmission nodes within the territory of Liaoning Province. The network has been upgraded to digital since June 1999. Instruments mainly include broadband (BB) and/or short period (SP) seismographs, with sampling frequency 50 Hz. Figure 2 is the distribution of these stations and their frequency response, together with the earthquakes under study, recorded by this seismological observation system.

To study the whole sequence of earthquakes one needs to ensure the completeness of the earthquake catalogue. For doing this, considering the methodology for identifying "repeating earthquakes" (as described in detail in the following sections), we applied a "multi-scale zooming-in" strategy. That is, we use the seismic stations located in a larger area (the whole Fig. 2) rather than just the "focused" region under consideration (the box with solid line in Fig. 2, or the region shown in Figs. 1 and 4). Next, to avoid the loss of "repeating events" near the border of the study region (the box in solid line in Fig. 2), we considered a somewhat larger region (the box with dashed line) encompassing it.

We selected the waveform data of the events with clear P phase pickings at no less than 3 stations for the period June 1999 to December 2006 within the spatial range 39.9 ∼ 41.3° N, 121.8 ∼ 123.6° E (the dashed box in Fig. 2). There are a total 1358 events (with maximum magnitude $M_L = 5.9$) occurring in this spatial range – southern Liaoning and its surrounding regions – in which the $M_L = 5.9$ event is just the $M_S = 5.4$ Xiuyan earthquake. As a reference, for the prediction of the Xiuyan earthquake and the follow-up studies see Appendix A. In the regional catalogue, the "default"

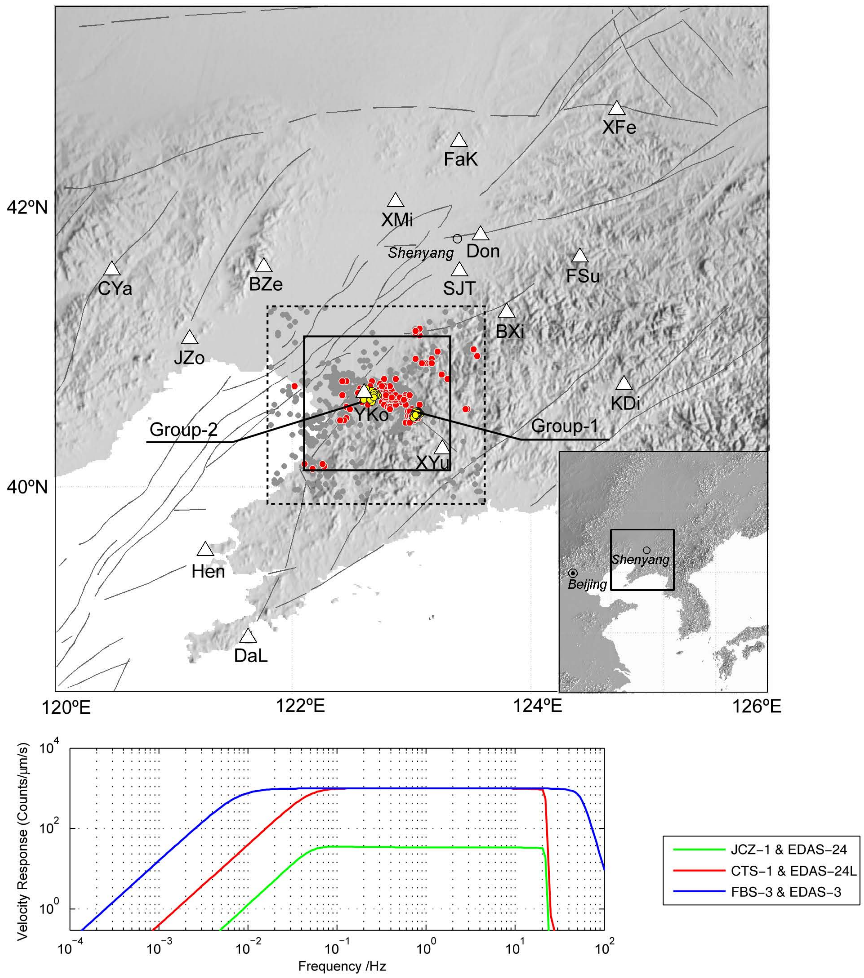

Fig. 2. (Top) Distribution of earthquakes and seismic stations used for this study. Earthquakes are shown by gray dots. Shown in red are the "repeating earthquakes" identified by waveform cross-correlation. Yellow dots show the two "multiplets" under consideration. Gray lines indicate tectonic faults. Box in the indexing figure indicates the whole region under consideration. In the region, box with solid lines highlights the study region (40.1 ∼ 41.1° N, 122 ∼ 123.4° E) as shown in Figs. 1 and 4, encompassed by a larger box with dashed lines (39.9 ∼ 41.3° N, 121.8 ∼ 123.6° E) to ensure the completeness of the "repeater" catalogue. Seismic stations are shown by triangles, with letters nearby indicating the name of the station. (Bottom) Instrumental response of the seismographs (from the Data Center of Liaoning Digital Seismograph Network).

magnitude is M_L. Accordingly, in the text and the figures it is noted by M_L or simply M. To check the completeness of the event sequence, Fig. 3 shows the frequency-magnitude distribution of these 1358 earthquakes, which indicates that the completeness magnitude can be safely selected as $M_L = 1.9$.

Before the cross-correlation of waveforms, pre-processing was taken using a 0.5 ∼ 5 Hz bandpass filter to BB recordings and a 1 ∼ 5 Hz bandpass filter to SP recordings. Jiang et al. (2008) discussed in detail the effect on the selection of "repeaters" by the mixture of BB and SP waveforms. The whole waveform composed of P, S, and coda phases was selected. Waveform was picked 4 s before the Pg arrival, and the whole waveform length was taken as 4 times of the S-P travel time difference. For the present station-epicenter distances, according to the empirical local knowledge of seismic observation, the S-P travel time difference can be roughly estimated by the apparent velocity 8 km s^{-1}. Sliding window was taken as 4 s less than the length of the whole waveform, sliding from the beginning point (4 s before the Pg arrival), with step of 1 sample. For regional seismic recordings, such processed waveform covers the whole wave train from P arrival to coda reverberations, while avoiding the disturbance from noise.

Among the 1358 events selected in this study, some thousands of preliminary pairs with separation distance (as reported in the regional bulletins) less than 20 km were constructed. Cross-correlating the waveforms of these preliminary pairs, there are 307 events recognized as "repeating

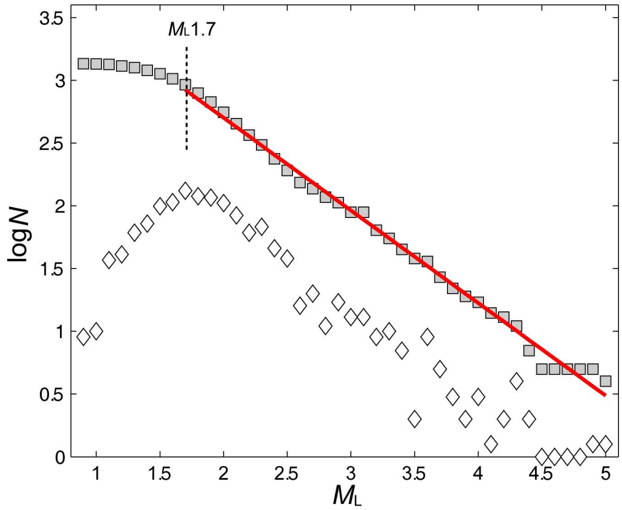

Fig. 3. Frequency-magnitude distribution of the events in the dashed box (39.9 ∼ 41.3° N, 121.8 ∼ 123.6° E) in Fig. 2, consisting of 1358 events, showing the completeness of the sequence selected. Light grey squares show the cumulative magnitude distribution, while white diamonds show the magnitude distribution itself (the differential distribution). Red solid line fits the Gutenberg-Richter's law. Completeness magnitude can be selected by visual inspection as $M_L = 1.7$ according to the end of the power-law-like frequency-magnitude distribution, seen both from the cumulative and the differential distribution curves. In the study, completeness magnitude is selected more conservatively as $M_L = 1.9$.

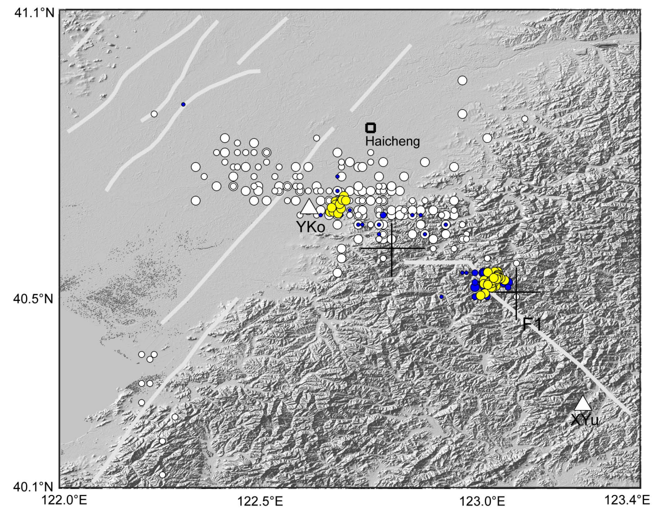

Fig. 4. Aftershocks of the 1975 Haicheng earthquake ($M_L \geq 3.0$, totaling 222 events, shown by white dots) and the 1999 Xiuyan earthquake ($M_L \geq 2.0$, totaling 82 events, shown by blue dots) as background of the "multiplets". Two groups of "multiplets" in the southern Liaoning region (shown by the solid box in Fig. 2) are shown by yellow dots. Stations in the surrounding of these "multiplets", YKo and XYu, are shown by white triangles. White thick line, indicated by F1, shows the Haicheng River-Dayang River fault. The two crosses in black represent the epicenters of the 1975 Haicheng earthquake and the 1999 Xiuyan earthquake, respectively.

events", with three or more stations having the (maximum sliding) cross-correlation coefficients larger than 0.8. Among these 307 "repeaters" which form "pairs" and/or "multiplets" with other events, there are 295 located within the solid box, the region under study. Such a "multi-scale zooming-in" strategy avoids the problems caused by the lack of available stations and the missing of "repeaters" near the boundary of the study region. From Figs. 2 and 4 it can be seen that there are only two stations (XYu and YKo) located in the study region, which means that if the distribution of stations and the distribution of earthquakes take the same area, then it is not possible to identify the "repeaters" according to the above-mentioned criteria.

4 Pre-, immediate-post-, and post-seismic slip indicated by a "multiplet"

There are quite a few different definitions of a "multiplet". The senso lato "multiplet" refers to the case that one event in a "multiplet" has at least one partner, while the senso stricto "multiplet" refers to the case that any event has partnership with every other one within the same "multiplet". A "multiplet" with n events is also called "n-plet". In this study we take the senso lato definition of a "multiplet". Tables A1 and A2, as well as Figs. A1 and A2, show two examples. One of them is a 57-plet that occurred from 1999 to 2004 near Xiuyan, the other one is a 19-plet near Yingkou. The locations of these two "multiplets" are shown in Fig. 4. These two "multiplets" locate near the source region (as indicated, indirectly but effectively, by the aftershock sequences shown on the map) of the 1975 Haicheng $M_s = 7.3$ earthquake (to the west) and the 1999 Xiuyan $M_s = 5.4$ earthquake (to the east), respectively. For the Xiuyan "multiplet" (shown in Table A1), there are 22 events before the occurrence of the 1999 Xiuyan earthquake and 35 aftershocks that followed. Taking the complete catalogue above $M_L = 1.9$, these two "multiplets" become a "52-plet" and a "15-plet", respectively.

The parameters chosen for the identification of "repeaters" are similar to those of Schaff and Richards (2004a) who found that "repeating events" meeting these criteria appear to be separated by no more than 1 km from each other. Therefore, for these magnitude events the source areas are not necessarily all overlapping on the same fault. Also, the cumulative slip is not necessarily occurring at the "same point" on the fault. Defining the "multiplets" in the senso lato sense means that every event is probably within 1 km of at least one other event but not all the other events. In this case, the cumulative slip reflects the process near the earthquake fault, or in the earthquake fault zone and its close surroundings. Nevertheless, the pre-shock change of "multiplets" is intrinsically different from conventional foreshocks since the

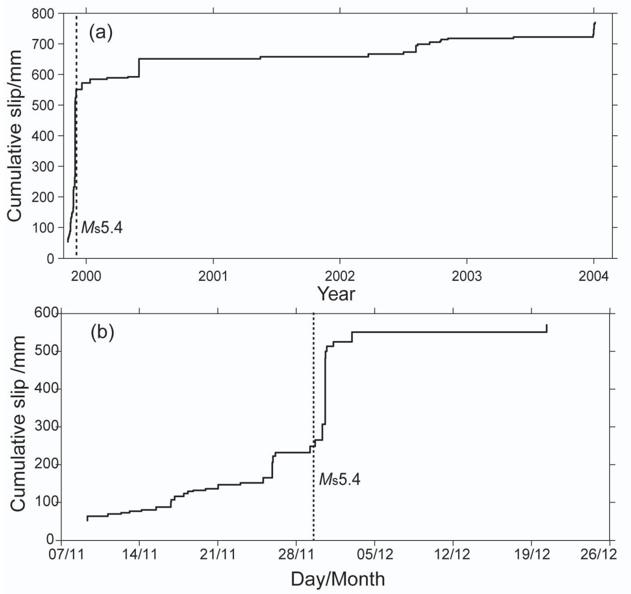

Fig. 5. **(a)** Cumulative slip plot for all the events of the Xiuyan 52-plet, with the vertical dashed line indicating the origin time of the 1999 Xiuyan $M_S = 5.4$ earthquake (which is not belonging to this 52-plet and accordingly not shown in the cumulative slip plot). **(b)** Zooming-in of Fig. 5a, with the vertical dashed line indicating the origin time of the 1999 Xiuyan earthquake.

"multiplets" deal with a special spatial range near an earthquake fault, while foreshocks may distribute in a wider area.

Similar to previous approaches (e.g., Li et al., 2007, 2009), estimation of slip is conducted in the following steps. Firstly, calculate seismic moment by magnitude of earthquakes via $\log M_0 = 16.1 + 1.5 M_L$ (Hanks and Kanamori, 1979). Next, radius r of the assumed circular rupture is estimated by $r = \left(7M_0 \big/ 16\Delta\sigma\right)^{1/3}$ (Kanamori and Anderson, 1975), in which stress drop is taken as $\Delta\sigma = 3\,\mathrm{MPa}$. Lastly, slip d is deduced by $d = M_0/\mu\pi r^2$ in which the rigidity of the source medium is taken as $\mu = 3\times10^{10}\,\mathrm{N\,m^{-2}}$. Obviously this calculation includes several assumptions and is not the direct estimate of slip amount. In principle, the calculation here is similar to the calculation of Benioff strain in that the source parameter, either slip in this case or Benioff strain, is not measured directly but calculated from magnitude.

Figure 5a shows the cumulative slip for all the events of the Xiuyan "multiplet", with the vertical dashed line indicating the origin time of the 1999 Xiuyan $M_S = 5.4$ earthquake. The Xiuyan main shock does not belong to this "multiplet", and thus not shown in the cumulative slip plot. But the increase of aftershocks caused by the main shock can be clearly seen in Fig. 5b, a zooming-in of Fig. 5a, which shows a clear immediate post-seismic change. Also from Fig. 5a and b, the Omori-law-like post-seismic relaxation process is clear.

5 Pre-shock accelerating slip?

Figure 6a is a further zooming-in of Fig. 5a and b. The red line indicates the fitting of the cumulative slip curve priori to the Xiuyan earthquake by $\Sigma d = A + B\,(t_0 - t)^m$, in which Σd is the cumulative slip, t_0 is the time of the Xiuyan earthquake (as shown by the vertical dashed lines), A and B are constants, and m is the coefficient indicating the overall property of the curve. Taking the experiences of the AMR investigation (e.g., Brehm and Braile, 1998; Bowman and King, 2001), if m is less than 1, then the curve is accelerating-like; if m is larger than 1, then the curve is relaxation-like; if m is near unity, then the curve is linear. In this fitting, the number of data points is 22, and $m = 0.57$, indicating an accelerating-like trend. Note that AMR for a long time scale and foreshock-like sequence for a short time scale has self-similar properties in the critical-point-like process approaching the earthquake. Tools for the identification of accelerating trend can be used for both cases, although the physics lying behind may differ.

A linear fitting has two free parameters to determine, while a power-law fitting has three or four, depending on whether the "failure time" t_0 is to be calculated. To avoid the problem of over-fitting, an additional consideration is the BIC gain that balances the residual of the fitting and the degrees-of-freedom of the model (Jiang and Wu, 2009). By definition, a reasonable fitting has to satisfy the criteria $\Delta\mathrm{BIC} \geq 0$. In the case of Fig. 6, $\Delta\mathrm{BIC} = 3.3$, indicating that acceleration is a better description than a simple linear increase.

As shown by Fig. 6b, the magnitude-time plot for these "repeaters" before the Xiuyan earthquake, the "accelerating-like process" as observed above, reflects only an overall trend over a pretty long time duration. In the perspective of earthquake forecast, the lack of data samples makes it hard to establish a baseline of slip rate before the main shock, therefore the observation here does not mean that a practical scheme for earthquake forecast could be obtained based on this acceleration-like property, albeit this is the best data we can get up to now.

As a comparison, Fig. 7 shows the cumulative slip plot for the Yingkou "multiplet". The red line indicates the fitting by the same equation as that in Fig. 6a, with t_0 set to be the time of the last event. The fitting obtains $m = 0.95$, indicating an overall near-linear increase. Also remarkably, the amplitude of the slip rate is significantly smaller than that indicated by the Xiuyan "multiplet", as can be seen from the slopes of Figs. 6a and 7a. Note that it has been a quarter century since the 1975 Haicheng earthquake, and the slip here is behaving in a different way from the post-seismic relaxation as shown by Fig. 5 as well as the previous observations of post-seismic variation (Schaff et al., 1998). To some extent, the comparison between the Xiuyan "multiplet" and the Yingkou "multiplet" indicates that, although data samples are still small, the pre-, immediate-post-, and post-seismic slip shown in the Xiuyan "multiplet" has physical clues for

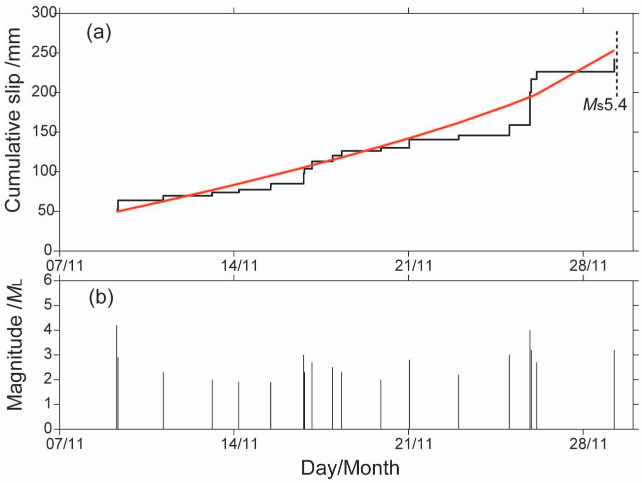

Fig. 6. (a) Power-law fit of the pre-shock cumulative slip curve, for the "repeaters" within the Xiuyan 52-plet, occurred before the Xiuyan earthquake. The power-law curve is represented by the red line, showing the accelerating-like behavior. This figure is a further zooming-in of Fig. 5a and b. **(b)** Magnitude-time plot of the "repeating earthquake sequence" in **(a)**. It is somehow similar to foreshock activities, but the spatial range is limited to the range of the "multiplet".

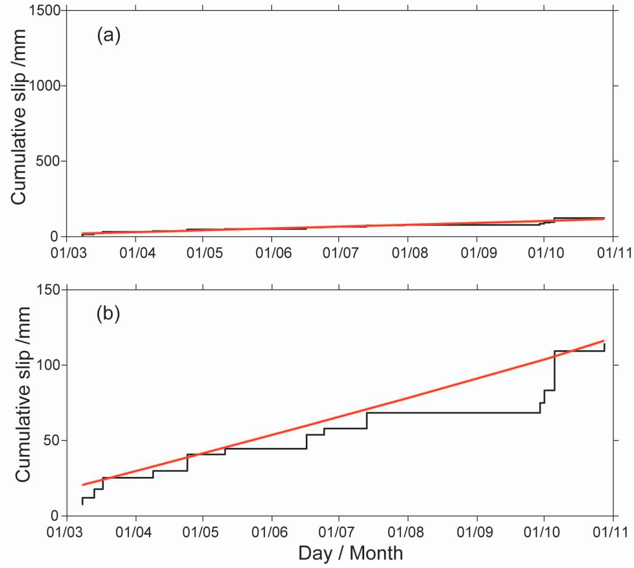

Fig. 7. (a) Cumulative slip plot for the Yinkou 15-plet, with the aspect of coordinates maintaining the same slope as that in Fig. 6a for comparison of the slip rate. **(b)** The same as **(a)**, with the vertical coordinate magnified by 10 times. Red line shows the fit of the cumulative slip curve.

the understanding of earthquake preparation. The relation between the pre-seismic accelerating-like slip observed here and other precursor-like anomalies reported (Fig. A3 and Table A3) needs further investigation. Note that earthquakes with clear pre-seismic changes and/or anomalies are not common characteristics; we are therefore not sure whether the observation here for the Xiuyan "multiplet" is valid for other earthquake cases.

6 Conclusions and discussion

"Repeating earthquakes", a concept having been proposed since decades ago based on waveform cross-correlation and accurate/precise location, has shown its potential in the assessment of earthquake recurrence and slip rates (Vidale et al., 1994; Nadeau et al., 1995; Igarashi et al., 2003) as well as the study of the physics of earthquake rupture (Anooshehpoor and Brune, 2001; Beeler et al., 2001; Sammis and Rice, 2001). In this study, by analyzing two "multiplets" in Liaoning Province, we provide a case of pre-, immediate-post-, and post-seismic slip revealed by "repeating earthquakes" associated with the 1999 Xiuyan earthquake. Somewhat interesting is the case of the accelerating-like cumulative-slip before this $M_S = 5.4$ earthquake. This accelerating-like process is near the earthquake fault or within the earthquake fault zone and its close surroundings. This approach has some similarities with the AMR studies in the perspective of the critical-point-like behavior in the earthquake preparation process, but deals with a short time scale. This approach shares some similarities with foreshock studies, but is different in that it deals with a special spatial range – the span of a "multiplet". The observation in this approach may have some relations with the precursors observed before the Xiuyan earthquake, but at the present time further investigation is needed, as the present approach provides at most a heuristic clue. Obviously, case studies have limited significance in the statistical perspective, and retrospective case studies especially have limited significance in the forecasting perspective. However, accumulation of cases of earthquakes plays an important role at the present stage for testing the physical models of earthquakes against real seismic data, and we are looking forward to more similar cases so that comparisons can be made.

Last but not least, accelerating slip (at any time scale) has shown to be a necessary but not sufficient condition for the occurrence (or forecast) of the forthcoming earthquake. Sometimes the observed accelerating cumulative energy release may be blocked by an asperity along the fault, and sometimes the acceleration might be followed by a silent earthquake, unfortunately not known, and then apparently the expected earthquake will not occur. It should be cautioned, therefore, that the results of the pre-shock acceleration from AMR revealed by seismicity to foreshocks, and from accelerating slip revealed by "repeaters" to accelerating process indirectly shown by other precursor data, are still not sufficient to lead to practical prediction of the "target" earthquake.

Appendix A

Background information

Appendix A provides the seismic waveforms (Figs. A1 and A2) and parameters (Tables A1 and A2) of the “multiplets” under study, together with the background information of the prediction of the 1999 Xiuyan earthquake (Fig. A3 and Table A3).

Table A1. Parameters of the Xiuyan “multiplet”.

No.	Date (yy-mon-d)	Origin Time (h-min-sec)	M_L	Rupture radius (m)	Slip (mm)
1	1999-11-09	07:07:21.20	4.2	715.5	52.1
2	1999-11-09	08:21:36.20	2.9	160.2	11.7
3	1999-11-11	03:55:08.40	2.3	80.3	5.8
4	1999-11-12	08:23:16.00	1.8	45.1	3.3
5	1999-11-13	02:58:03.80	2.0	56.8	4.1
6	1999-11-14	04:40:06.20	1.9	50.7	3.7
7	1999-11-15	11:17:33.80	1.9	50.7	3.7
8	1999-11-15	11:32:12.70	1.9	50.7	3.7
9	1999-11-16	18:57:48.50	3.0	179.7	13.1
10	1999-11-16	19:52:03.70	2.3	80.3	5.8
11	1999-11-17	03:09:31.40	2.7	127.2	9.3
12	1999-11-17	22:59:50.80	2.5	101.1	7.4
13	1999-11-18	07:36:50.00	2.3	80.3	5.8
14	1999-11-18	19:04:39.70	1.6	35.9	2.6
15	1999-11-19	21:25:17.00	2.0	56.8	4.1
16	1999-11-21	00:50:01.90	2.8	142.8	10.4
17	1999-11-23	00:07:33.30	2.2	71.6	5.2
18	1999-11-25	00:59:19.20	3.0	179.7	13.1
19	1999-11-25	20:47:48.50	4.0	568.4	41.4
20	1999-11-25	22:08:12.40	3.2	226.3	16.5
21	1999-11-26	03:18:23.30	2.7	127.2	9.3
22	1999-11-29	05:56:59.90	3.2	226.3	16.5
23	1999-11-29	16:43:51.60	3.2	226.3	16.5
24	1999-11-30	07:52:55.80	4.0	568.4	41.4
25	1999-11-30	14:06:55.10	4.9	1601.8	116.5
26	1999-11-30	14:09:36.60	4.3	802.8	58.4
27	1999-11-30	14:35:12.40	3.3	253.9	18.5
28	1999-11-30	17:40:34.50	3.0	179.7	13.1
29	1999-12-01	07:51:29.00	2.9	160.2	11.7
30	1999-12-02	23:16:21.00	3.6	358.6	26.1
31	1999-12-20	08:34:03.40	3.4	284.9	20.7
32	2000-01-12	13:07:24.50	3.0	179.7	13.1
33	2000-03-01	04:38:29.10	2.0	56.8	4.1
34	2000-04-30	15:48:31.40	1.9	50.7	3.7
35	2000-06-01	13:18:04.80	3.1	201.7	14.7
36	2000-06-01	13:33:58.30	1.9	50.7	3.7
37	2000-06-01	13:57:47.80	3.2	226.3	16.5
38	2000-06-01	14:46:13.20	3.3	253.9	18.5
39	2000-06-01	15:00:53.20	2.2	71.6	5.2
40	2001-05-16	05:44:23.40	2.4	90.1	6.6
41	2002-03-23	05:38:05.40	2.1	63.8	4.6
42	2002-03-23	05:50:53.10	2.1	63.8	4.6
43	2002-07-02	07:00:47.20	2.4	90.1	6.6
44	2002-08-07	06:11:11.20	3.4	284.9	20.7
45	2002-08-11	14:04:24.50	2.0	56.8	4.1
46	2002-09-15	12:33:58.50	2.4	90.1	6.6
47	2002-10-15	13:11:02.40	1.9	50.7	3.7
48	2002-10-18	13:18:02.50	2.3	80.3	5.8
49	2002-11-07	01:16:32.40	1.6	35.9	2.6
50	2003-05-14	15:14:21.40	2.2	71.6	5.2
51	2003-12-30	09:02:15.60	1.6	35.9	2.6
52	2003-12-30	13:06:21.30	1.9	50.7	3.7
53	2003-12-30	13:39:38.80	1.7	40.2	2.9
54	2003-12-31	15:24:53.10	2.0	56.8	4.1
55	2003-12-31	15:52:04.20	2.9	160.2	11.7
56	2004-01-02	00:38:38.00	3.3	253.9	18.5
57	2004-01-04	06:58:24.00	2.3	80.3	5.8

Table A2. Parameters of the Yingkou “multiplet”.

No.	Date (yy-mon-d)	Origin Time (h-min-sec)	M_L (m)	Rupture radius (mm)	Slip (mm)
1	2004-03-07	21:45:42.80	2.5	101.1	7.4
2	2004-03-08	00:37:13.10	2.1	63.8	4.6
3	2004-03-08	14:37:14.90	1.8	45.1	3.3
4	2004-03-13	06:04:49.30	2.3	80.3	5.8
5	2004-03-17	03:22:32.90	2.5	101.1	7.4
6	2004-03-17	03:35:55.40	1.8	45.1	3.3
7	2004-04-08	15:28:44.40	2.1	63.8	4.6
8	2004-04-24	00:36:55.20	2.2	71.6	5.2
9	2004-04-24	01:04:54.00	2.3	80.3	5.8
10	2004-05-10	23:47:27.60	1.9	50.7	3.7
11	2004-06-16	10:44:14.80	2.7	127.2	9.3
12	2004-06-24	08:14:47.00	2.0	56.8	4.1
13	2004-07-13	12:21:59.90	2.8	142.8	10.4
14	2004-07-30	07:26:01.80	1.7	40.2	2.9
15	2004-09-29	03:34:59.90	2.4	90.1	6.6
16	2004-10-01	03:01:23.90	2.6	113.4	8.3
17	2004-10-03	17:58:21.30	1.8	45.0	3.3
18	2004-10-05	16:49:53.90	3.6	358.6	26.1
19	2004-10-28	01:24:56.30	2.2	71.6	5.2

Table A3. References related to the prediction of the 1999 Xiuyan earthquake.

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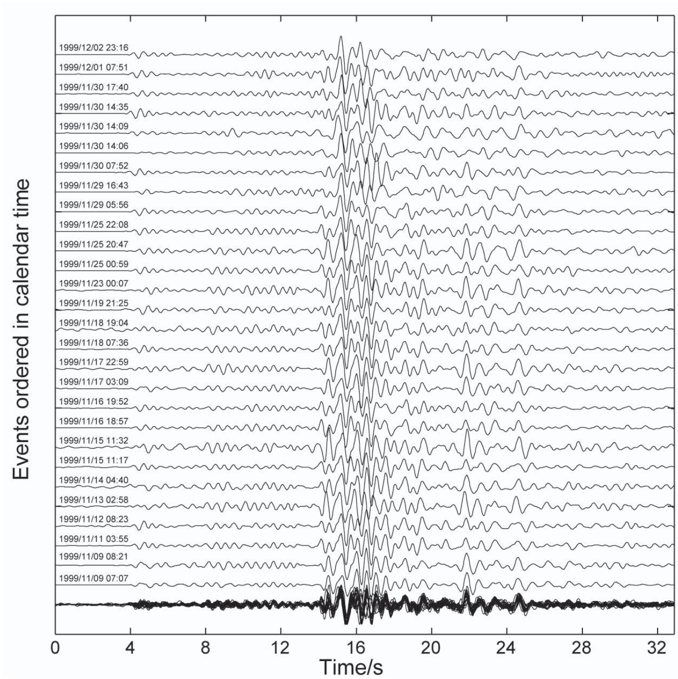

Fig. A1. Filtered seismograms of the Xiuyan "multiplet" recorded at the Yingkou (YKo) station. The figure shows part of the seismograms recorded by the Yingkou station (YKo, BB seismograph), in which "part of" means that for the 57-plet, only the seismograms of the first 31 events before and immediately after the Xiuyan earthquake are shown. In the figure, each trace has been normalized and pre-processed by a 0.5 ∼ 5 Hz band pass filter. Bottom trace is the stacking of all the above traces. The clearness of the stacked trace indicates the similarity of the waveforms. Note that the "repeaters" are identified by the criteria that filtered waveforms of at least 3 stations (not necessarily including the YKo station) have the cross-correlation coefficients no less than 0.8. For some of the events, there are no waveform recordings at the YKo station.

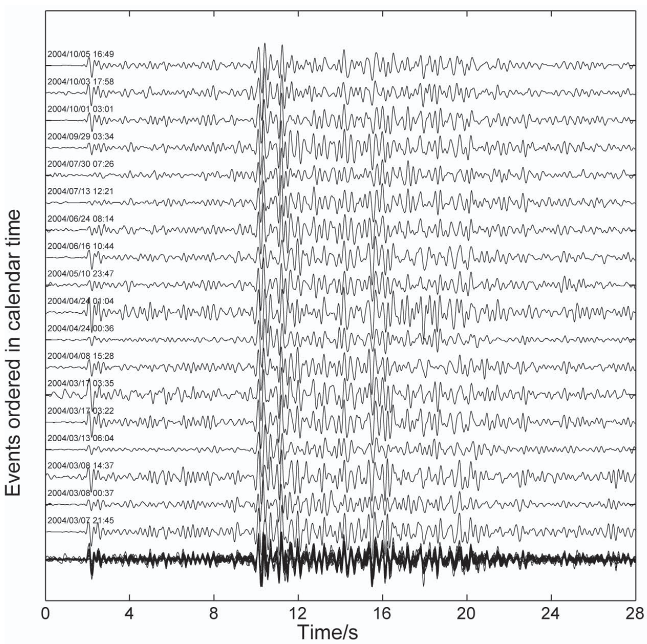

Fig. A2. Filtered seismograms of the Yingkou "multiplet" recorded at the Xiuyan (XYu) station, with the bottom trace being the stacking of all the seismograms. The "repeaters" are identified by the criteria that filtered waveforms of at least 3 stations (not necessarily including the XYu station) have the cross-correlation coefficients no less than 0.8. For some of the events, there are no waveform recordings at the XYu station.

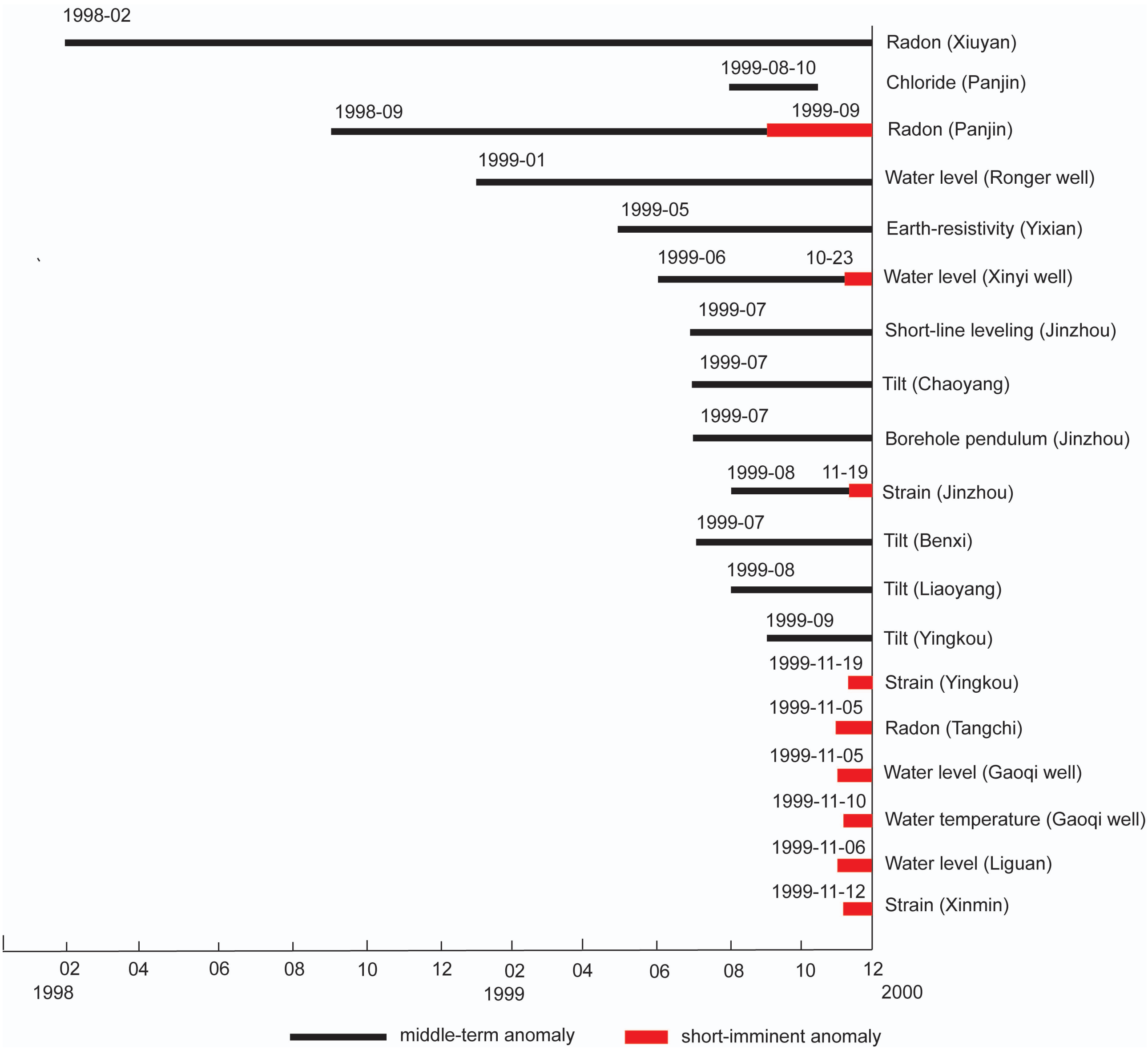

Fig. A3. Temporal process of registered precursory-like anomalies (with the name of stations in the parentheses), either by forward analysis or by retrospective analysis (based on Zhang, 2004, and the references listed in Table A3).

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