Strong Circular Arcs and Lines of Earthquakes Around Taiwan

台灣強地震圓弧與強地震線之研究

(Presented at the Department of Earth Sciences, National Central University, Taiwan, ROC. March 31,2017)

Speaker:

Hin-Chi Lei

Professor

Dept Civil Engrg,National Central University, Taiwan, ROC

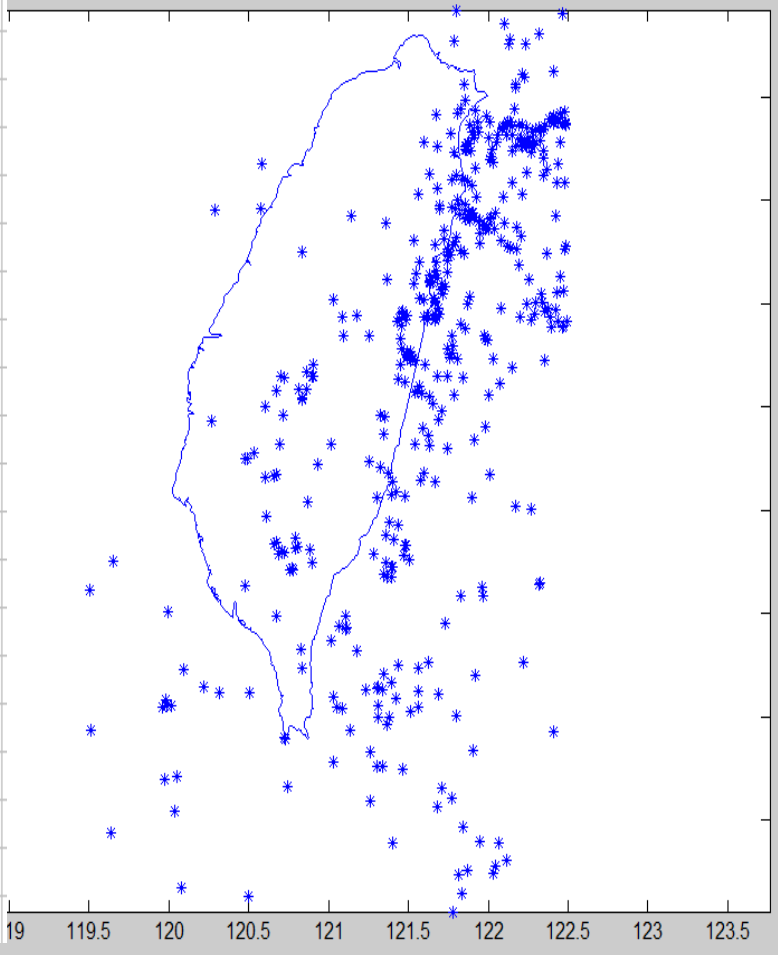
李顯智

國立中央大學 土木工程研究所 台灣 中華民國

NCUCE

Ordinary Outlook of the data from Earthquake Catalog

	1	2	3	4	5	6	7	8	9	10
1	121.8987	24.8283	1999	1	1	9	34	56.2100	80.7300	4.4000
2	121.9178	22.1973	1999	1	1	12	56	3.0800	60.6700	3.2000
3	121.6840	21.5632	1999	1	1	17	24	5.0900	10	3.2000
4	121.8337	21.1433	1999	1	1	19	12	18.6300	12.7300	3.6000
5	120.8617	23.5835	1999	1	2	5	5	46.4500	5.0300	3.1000
6	120.8048	22.8255	1999	1	2	6	52	27.1200	15.4600	3.4000
7	122.3148	25.3050	1999	1	2	7	15	31.1300	234.0400	3.8000
8	122.1015	24.3908	1999	1	2	7	21	40.8500	56.7800	3
9	121.6645	24.2842	1999	1	2	7	59	57.3400	21.8900	3.2000
10	121.7638	24.2360	1999	1	2	9	15	55.3500	13.2000	4.1000
11	121.3657	22.6785	1999	1	2	11	52	24.8600	15.6500	3
12	121.9023	24.4362	1999	1	2	22	15	36.3800	12.7400	3
13	121.7822	21.0557	1999	1	2	23	27	24.1700	7.0600	3.5000
14	121.7517	24.2535	1999	1	3	0	38	43.6700	14.5100	3.2000
15	121.6815	23.6483	1999	1	3	1	22	46.9900	27.5400	3.1000
16	121.8847	24.4022	1999	1	3	12	19	13.6000	7.6900	3.5000
17	122.4227	23.9725	1999	1	3	20	55	45.3200	0.6100	4.1000
18	122.4125	21.9293	1999	1	3	23	4	25.8800	2	3.8000
19	121.7573	23.7388	1999	1	4	0	27	26.4900	30.5700	3.2000
20	122.3275	24.7888	1999	1	4	5	54	45.4200	8.4600	3.3000



1999/01 to 1999/05 events with M>3

NCUCE

Double-Convex Strong Circular Arcs of Earthquakes before the 2016 Mei-Long Earthquake

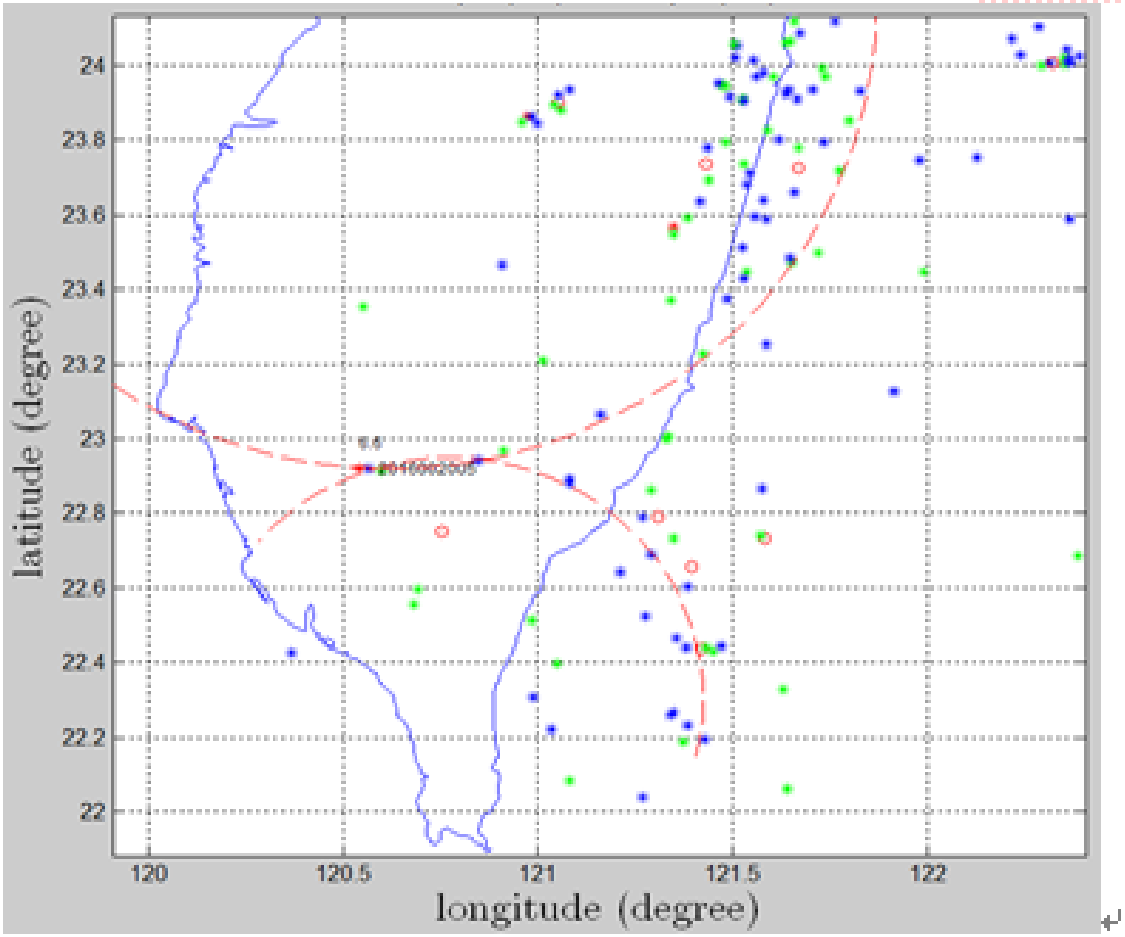


Fig. 32 An event with M=6.6 at one of the two intersection points of two SCAE. It is at the western ends of these two SCAE and occurred on 2016/2/6 in Kaohsiung.

The M≧4.6 events occurred 5 years before the 2016 Mei-Long earthquake.

Strong circular arcs of earthquakes: **circular arc containing 5^+ uniform spatial points with** M≧4.6 events happened nearby in N years. (N=5 at this stage of research, N may be changed slightly after more detailed studies have been done in the future.)

Red stars : M≧6.4 events (*)

Red circles : 6.39≧M≧5.8 events (o)

Blue stars : 5.79≧ M≧4.8 events (*)

Green stars : 4.79≧ M≧4.6 events (*)

Abstract

- Circular and Linear distribution patterns of earthquakes are important.
- All of the 59 strong earthquakes ($M \geqq 5.99$, 1977-2016) around Taiwan ($120^{o}E$-$122.5^{o}E$, $21.5^{o}N$-$25.5^{o}N$) studied by us occurred near to ($\leqq 70km$) some intersection points of (secondary) strong circular arcs or (secondary) strong lines of earthquakes with $M \geqq 4.8$ ($M \geqq 4.6$).

(Presented at "The 40th National Conference on Theoretical and Applied Mechanics, Hsinchu, Taiwan, ROC. November 25-26, 2016")

- (New Results) Almost all of the 59 strong earthquakes occurred around some double convex strong circular arcs of earthquakes.

Circles, Circular Arcs and Lines of Earthquakes Around Taiwan

Hin-Chi Lei*

Department of Civil Engineering, National Central University

*Corresponding Author: E-mail: hinchili@cc.ncu.edu.tw

Abstract

In a recent paper [1] the concepts of strong circular arcs and lines of earthquakes are proposed. Many examples of strong circular arcs of earthquakes were studied. It was found that they are important in the analysis of strong earthquakes. In this paper we provide more concrete examples and new ideas. First, it is found that, around Taiwan, most of the strong events with magnitudes over 5.8 in the last 43 years can be grouped into finite numbers of circles and lines. Second, in addition to the 14 arcs reported in [1, 2], much more new arcs and lines related to the strong earthquakes around Taiwan are reported in this article. In particular, it is found that almost all of the 59 strong earthquakes studied by us occurred around some intersection points of strong circular arcs or strong lines of earthquakes with M≧4.6. A three-step method is also proposed for the prediction of the future strong earthquakes.

Keywords: circular arc of earthquakes, line of earthquakes, circle of earthquakes

the last 43 years occurred near to some intersection points of strong circular arcs or strong lines of earthquakes with magnitudes over 4.6. These might be caused by the interactions of different stress concentration processes in different directions. The lines of earthquakes in this paper are horizontal while those in [1, 3] are vertical. A three-step method is also proposed for the prediction of the future strong earthquakes.

2. Fracture Mechanical Interpretation

In [1] we used an example from fracture mechanics to illustrate the importance of distribution pattern of earthquakes. Apart of the ideas in [1] is quoted below.

A row of 15 micro-voids in a tensile plate is shown in Fig. 1. If the width of the plate is w, the diameter of each of these micro-voids is 0.001*w, the thickness of the plate is b then the deducted area of the middle cross section is just 98.5% of the undamaged cross section area. This plate could be thought as nearly perfect if only the deducted area is considered. However, the plate is in fact

Circles, Circular Arcs and Lines of Earthquakes Around Taiwan

Hin-Chi Lei*

Department of Civil Engineering, National Central University

*Corresponding Author: E-mail: hinchili@ce.ncu.edu.tw

Abstract

In a recent paper [1] the concepts of strong circular arcs and lines of earthquakes are proposed. Many examples of strong circular arcs of earthquakes were studied. It was found that they are important in the analysis of strong earthquakes. In this paper we provide more concrete examples and new ideas. First, it is found that, around Taiwan, most of the strong events with magnitudes over 5.8 in the last 43 years can be grouped into finite numbers of circles and lines. Second, in addition to the 14 arcs reported in [1, 2], much more new arcs and lines related to the strong earthquakes around Taiwan are reported in this article. In particular, it is found that almost all of the 59 strong earthquakes studied by us occurred around some intersection points of strong circular arcs or strong lines of earthquakes with $M_W \geq 4.6$. A three-step method is also proposed for the prediction of the future strong earthquakes.

Keywords: circular arc of earthquakes, line of earthquakes, circle of earthquakes

1. Introduction

In a recent conference paper [1] the importance of circular arcs and lines of earthquakes was reported. The occurrences of them show us the locations of the stress localization in the crust. Many strong circular arcs of earthquakes in Taiwan over the past 43 years were found. For the 14 arcs we had studied [1, 2], after the appearances of 70% of them strong events with $M_W \geq 5.8$ occurred close to the arcs within 6 months.

In this paper more new results are reported. First, it is found that, around Taiwan, most of the 182 strong events with magnitudes over 5.8 in the last 43 years can be grouped into 10 circles and 10 lines. So, it is shown that *the locations of the strong earthquakes are not randomly distributed*. These circles and lines show us the previous locations of stress concentrations in the crust. The probability of occurrence of strong earthquakes along them was much higher than the probability for strong earthquakes in other places for the past 43 years. Second, in addition to the 14 arcs reported in [1, 2], much more new arcs and lines related to the strong earthquakes around Taiwan are reported in this article. In particular, it is found that almost all of the 59 studied strong earthquakes with $M_W \geq 5.99$ around Taiwan over the last 43 years occurred near to some intersection points of strong circular arcs or strong lines of earthquakes with magnitudes over 4.6. These might be caused by the interactions of different stress concentration processes in different directions. The lines of earthquakes in this paper are horizontal while those in [1, 3] are vertical. A three-step method is also proposed for the prediction of the future strong earthquakes.

2. Fracture Mechanical Interpretation

In [1] we used an example from fracture mechanics to illustrate the importance of distribution pattern of earthquakes. A part of the ideas in [1] is quoted below.

A row of 15 micro-voids in a tensile plate is shown in Fig. 1. If the width of the plate is w, the diameter of each of these micro-voids is $0.001*w$, the thickness of the plate is b then the deducted area of the middle cross section is just 98.5% of the undamaged cross section area. This plate could be thought as nearly perfect if only the deducted area is considered. However, the plate is in fact highly damaged due to the singularity effect caused by the special *pattern of distribution of micro-voids*. On the other hand, fifteen randomly distributed micro-voids cannot create this degree of damage. So, when analyzing the weakness caused by the defects in materials or structures, not only the numbers, the sizes, the orientations and the shapes, but also the *distribution patterns* of the defects should be considered. Under this context, the significance of the circular arcs of earthquakes can be clarified. That is, when analyzing the damages of the crust caused by earthquakes, not only the number and the magnitudes of the earthquakes, but also the *distribution patterns of the earthquakes* should be considered. For example, the damage to the crust caused by a circular arc of 6 earthquakes of magnitude 5 should be much larger than that by a set of 6 randomly distributed events with the same magnitude. The usefulness of this idea had been confirmed by our research results about the strong circular arcs of earthquakes [1, 2] and the vertical chains of earthquakes [1, 3]. It is also interesting to note that the concept of "density of microcracks" is a basic quantity in the subject of Damage Mechanics. From the above reasoning, it is clear that the concept of "density of microcracks" should be used with caution. In fact, a piece of material containing an array of microcracks can have a very low

1) Existing Curvilinear Spatial patterns of Earthquakes

Alignments of Microearthquakes:

Along some active faults we can see clear alignments of microearthquakes. (K. Oike 1976, Mizoue and Nakamura 1976, Wada 1975)

Nearly Conjugate Bands of Moderate and Small Earthquakes:

Within a certain period before the large earthquakes, the regional moderate and small earthquakes were often distributed in **narrow bands**. …. mainshock is located at their intersection…….the bands are usually several hundred kilometers long.....the bands are generally formed 1-3 years before the mainshock (Zhangli Chen et al. 1984)

Aligments of Microearthquakes

(K. Oike 1976, Mizoue and Nakamura 1976, Wada 1975)

Along some active faults we can see clear alignments of microearthquakes. In other cases, active faults or tectonic lines are clear boundaries between a very active region and a quiet region. …… Thus we can find boundaries of crustal blocks not only by the geological surveys on the surface but also by the observations of microearthquakes.

Nearly Conjugate Bands of Moderate and Small Earthquakes

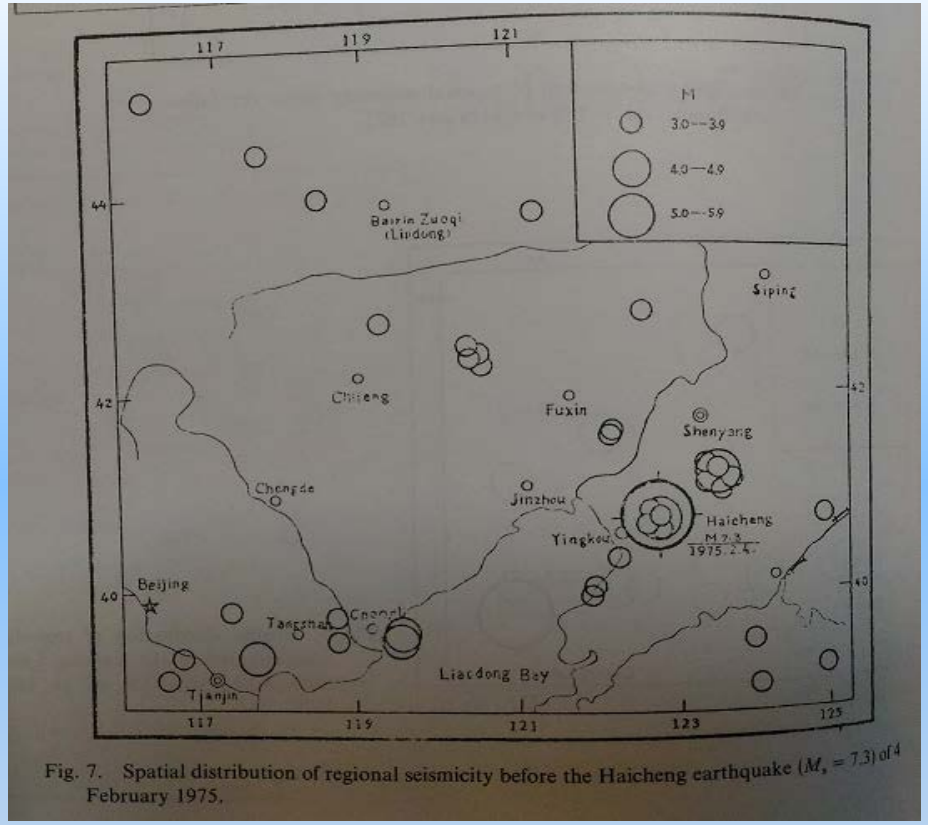


Fig. 7. Spatial distribution of regional seismicity before the Haicheng earthquake ($M_s = 7.3$) of 4 February 1975.

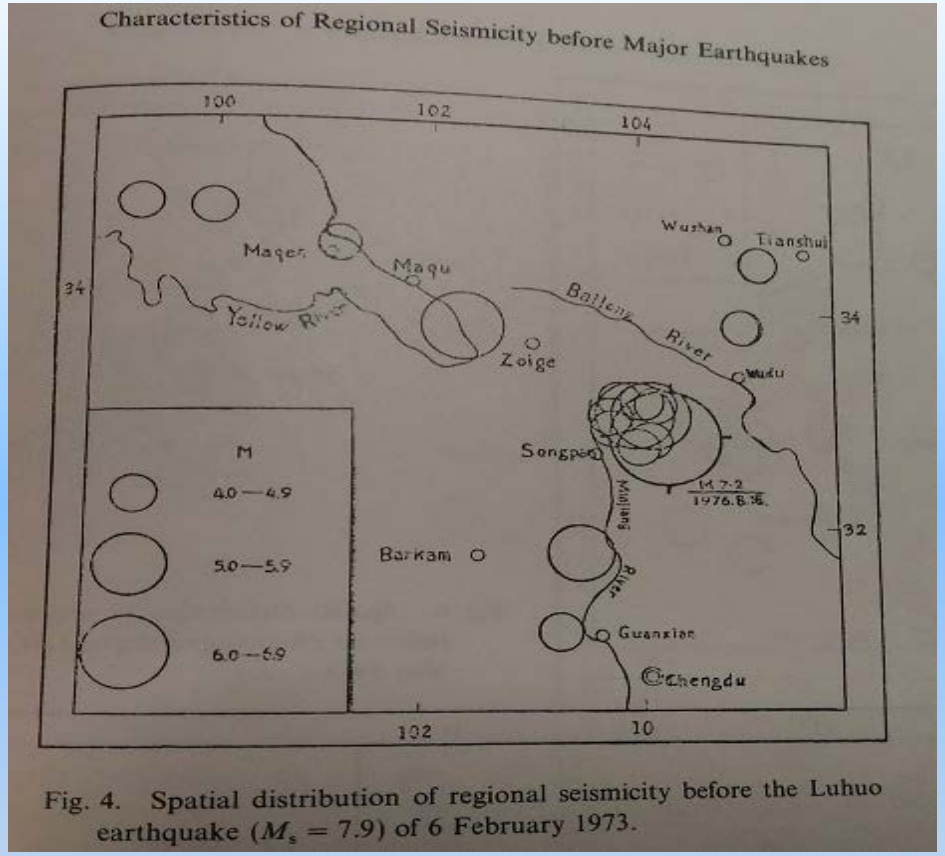


Fig. 4. Spatial distribution of regional seismicity before the Luhuo earthquake ($M_s = 7.9$) of 6 February 1973.

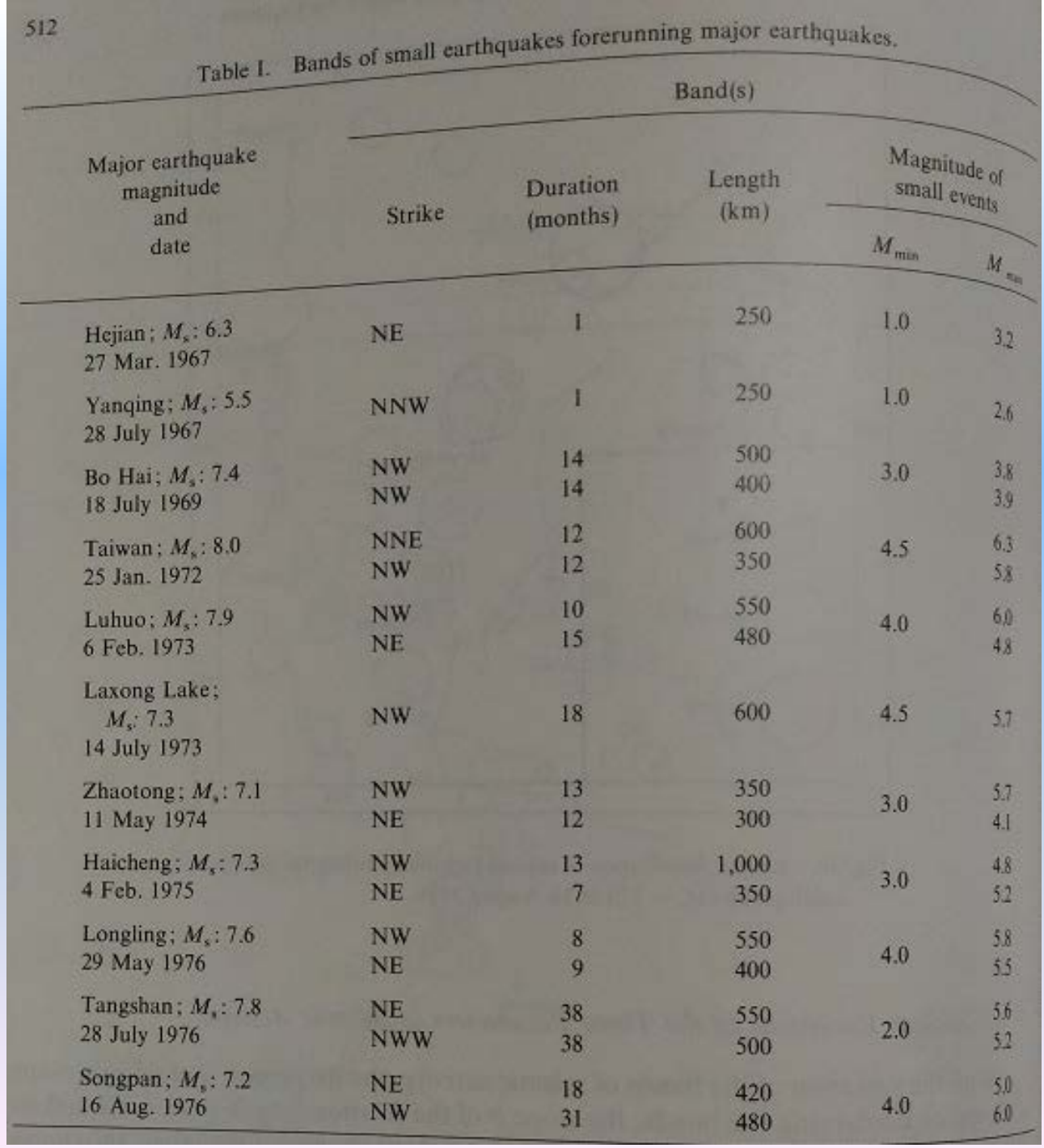
Nearly conjugate bands of earthquakes before 8 major earthquakes were reported.

Zhangli Chen et al (1984), Characteristics of regional seismicity before major earthquakes, Earthquake Prediction, Proceedings of the International Symposium on Earthquake Prediction, Terra Scientific Publishing Company, Tokyo, UNESCO, Paris.

NCUCE

The detailed distribution patterns of the events along the bands are missing.

In our works reported below more concrete description are given. 59 example are found so far.

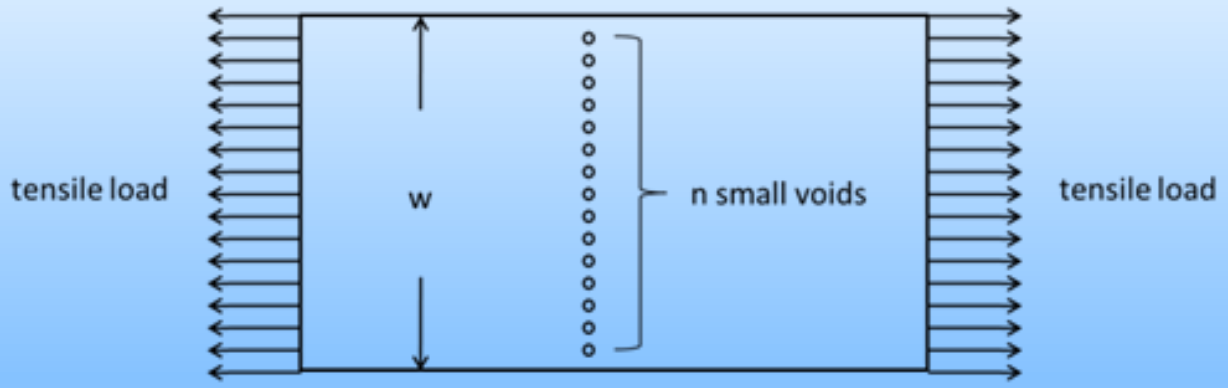


512

Table I. Bands of small earthquakes forerunning major earthquakes.

Major earthquake magnitude and date	Band(s) Strike	Duration (months)	Length (km)	Magnitude of small events M_{min}	M_{min}
Hejian; M_s: 6.3 27 Mar. 1967	NE	1	250	1.0	3.2
Yanqing; M_s: 5.5 28 July 1967	NNW	1	250	1.0	2.6
Bo Hai; M_s: 7.4 18 July 1969	NW NW	14 14	500 400	3.0	3.8 3.9
Taiwan; M_s: 8.0 25 Jan. 1972	NNE NW	12 12	600 350	4.5	6.3 5.8
Luhuo; M_s: 7.9 6 Feb. 1973	NW NE	10 15	550 480	4.0	6.0 4.8
Laxong Lake; M_s: 7.3 14 July 1973	NW	18	600	4.5	5.7
Zhaotong; M_s: 7.1 11 May 1974	NW NE	13 12	350 300	3.0	5.7 4.1
Haicheng; M_s: 7.3 4 Feb. 1975	NW NE	13 7	1,000 350	3.0	4.8 5.2
Longling; M_s: 7.6 29 May 1976	NW NE	8 9	550 400	4.0	5.8 5.5
Tangshan; M_s: 7.8 28 July 1976	NE NWW	38 38	550 500	2.0	5.6 5.2
Songpan; M_s: 7.2 16 Aug. 1976	NE NW	18 31	420 480	4.0	5.0 6.0

2) Array of Earthquakes as Stress Localization Indicator of the Crust

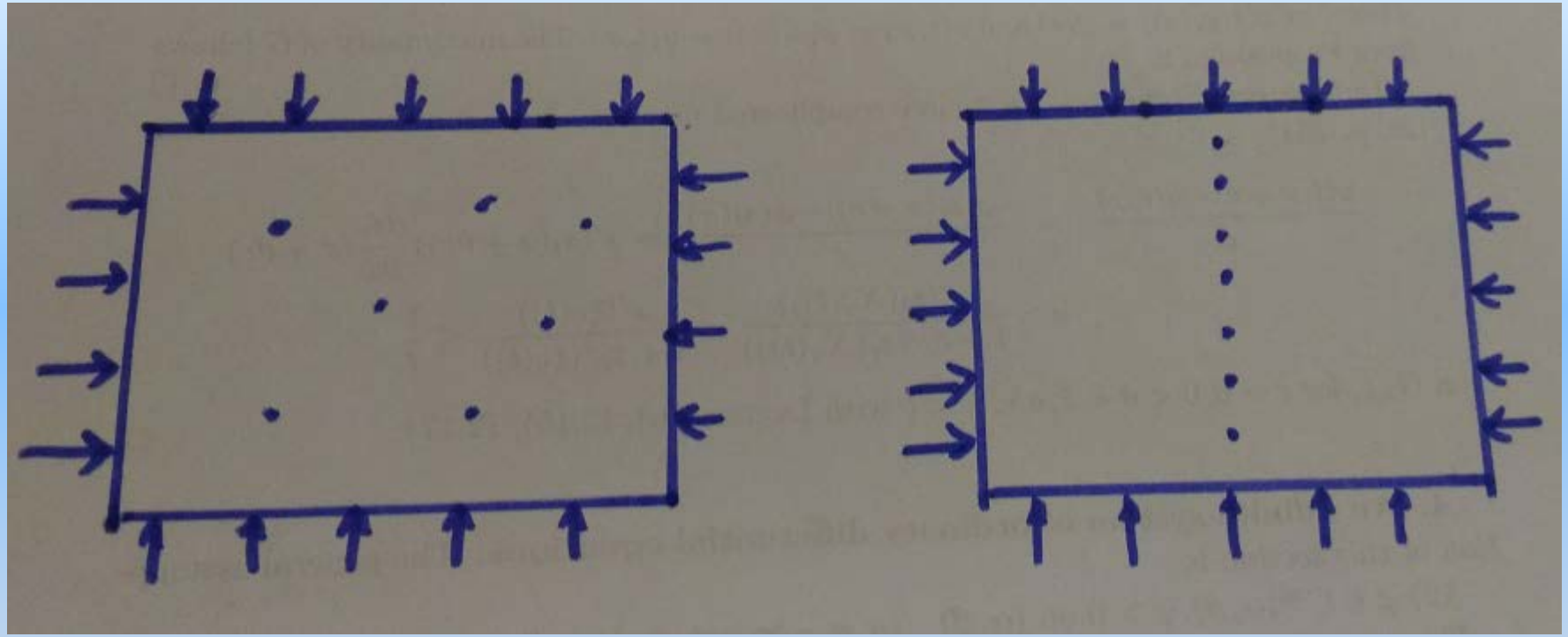


stress localization occurs along the arrey of defects.

Linear or Curvilinear distribution patterns of the defects

Linear or Curvilinear distribution patterns of the earthquakes

Two compressive plates with 7 small void



Which one will develop stress localization?

The one with linear (or curvilinear) distribution of voids will.

Tension gash array in incipient shear zone

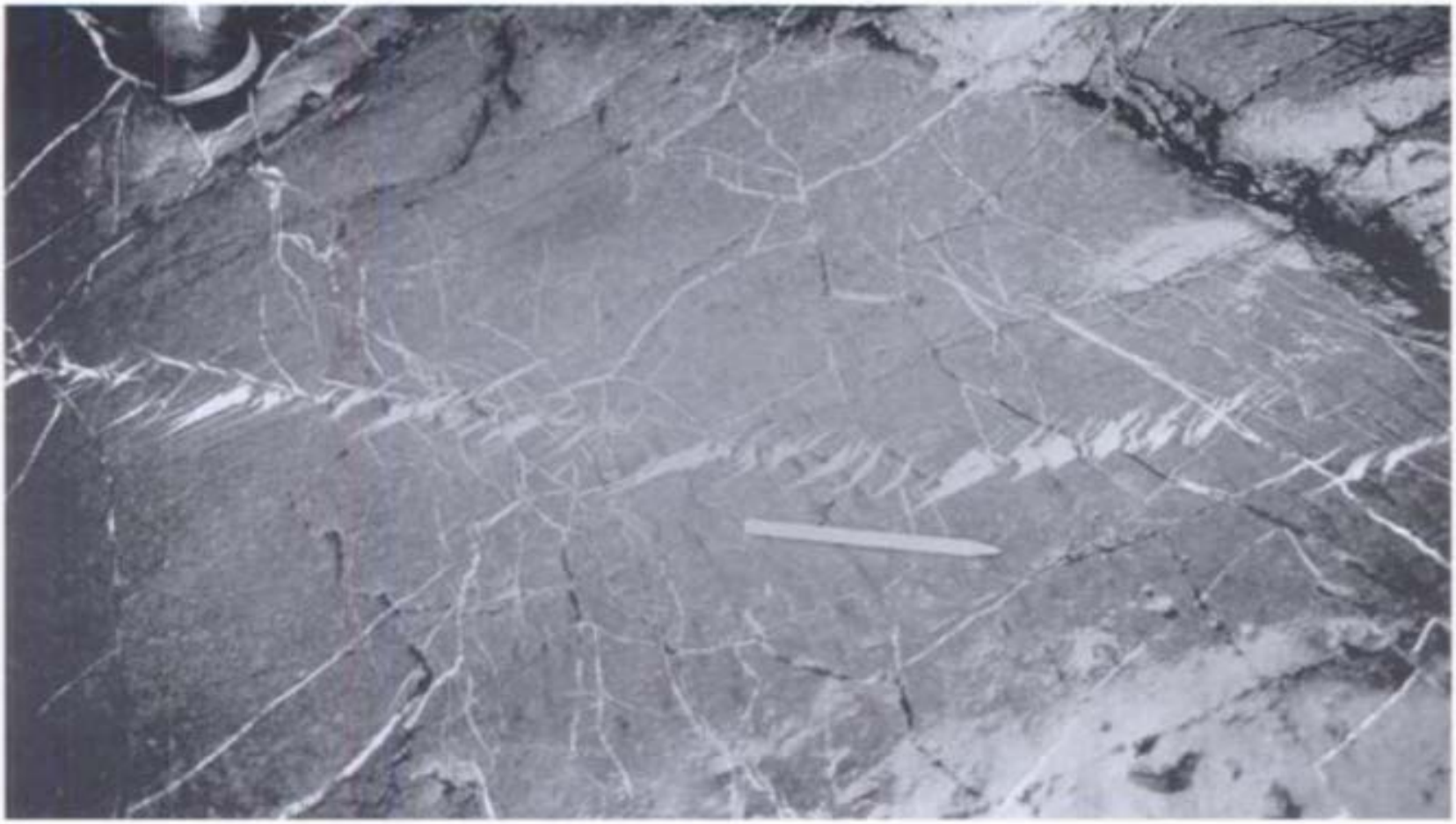
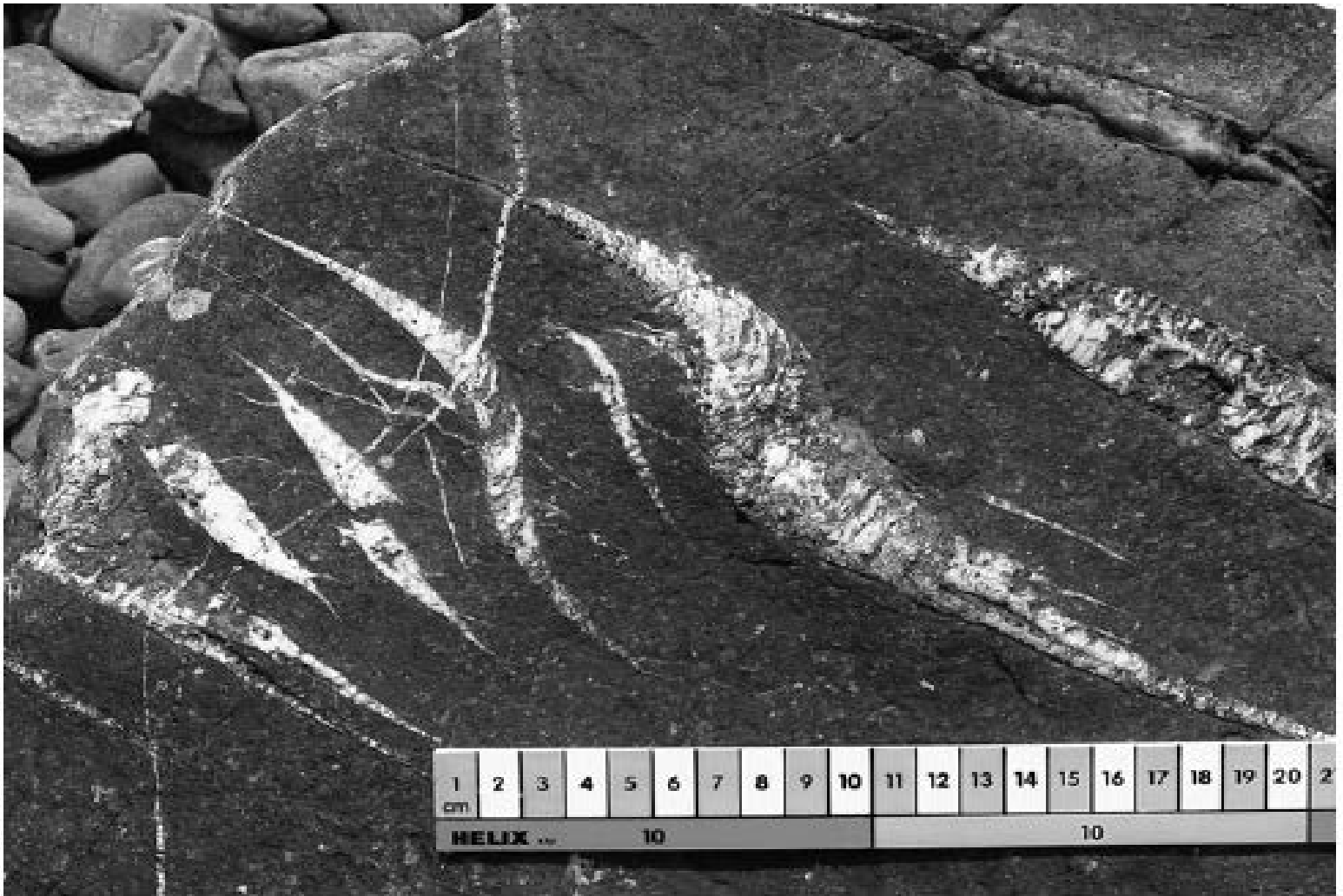


Fig. 3.25. Photograph of a tension gash array in an incipient shear zone, Hartland Quay, Cornwall. Sense of slip: left lateral. (Photograph by Simon Cox.)

Scholz, C.H., "The Mechanics of Earthquakes and Faulting" (second edition), Cambridge University Press, Cambridge, United Kingdom (2002).

Tension gash array in incipient shear

Sigmoidal tension gash array at Marloes Sands, SW Wales. Ruler marked in cm.



Difference: tension gash array and array of earthquakes

1. The tension gash array in the photograph is distributed *on the surface*.

2. Circular arcs and Lines of earthquakes analyzed by us are buried *inside the crust*.

3. They can be found by data mining of the earthquake catalog .

3) Indicator of the Stress Localization in the Crust --SCAE, SSCAE, SLE and SSLE

Strong circular arc of earthquakes (SCAE)

Secondary strong circular arc of earthquakes (SSCAE)

Strong line of earthquakes (SLE)

Secondary strong line of earthquakes (SSLE)

Information carried by SCAE, SSCAE, SLE and SSLE

Recent location and potential of the stress localization in the crust.

(location prediction of earthquake)

(x, y)

Potential : the total length and total number of uniform spatial points of a SCAE (or SLE) and the magnitudes of the events along the SCAE (or SLE) may provide us some useful information about the potential accumulated in the area around the SCAE (or SLE).

Strong Circular Arc of Earthquakes (SCAE)

- 5^+ uniformly distributed spatial points along a horizontal circular arc (50km < length < 400km)
- Near to each spatial point there is at least one event with M 4.8^+ and depth <50km occurred in 5 years (could be modified to 3 or 4 years in future, after more precise studies have been carried out)
- The occurrence time of the fifth spatial point with at least one M 4.8^+ event nearby is called the confirming time of the strong circular arc of earthquakes (SCAE)

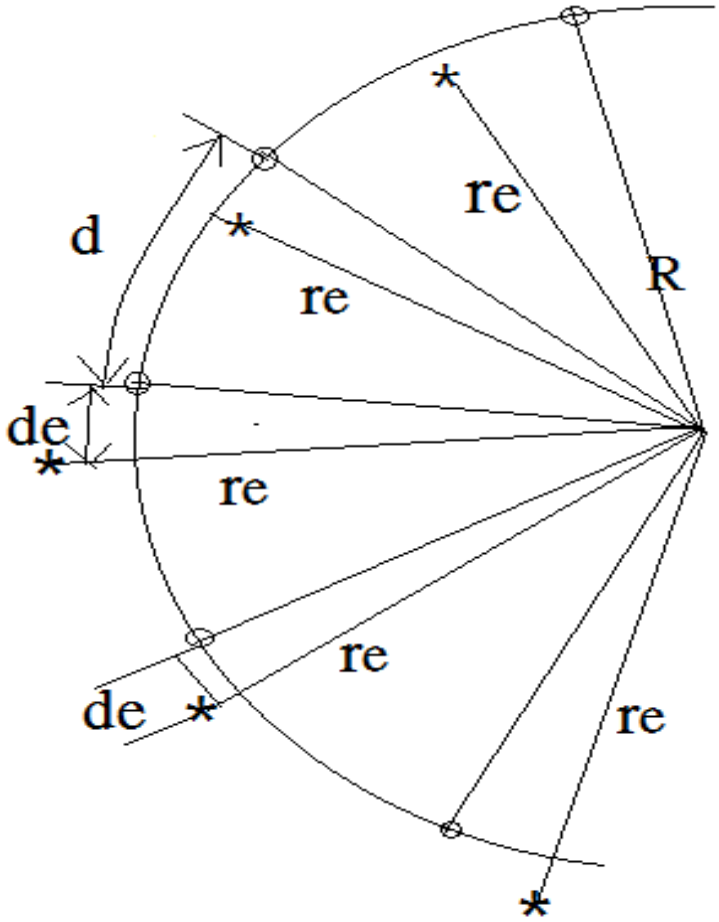
More Precise Descriptions of the Distances between the Spatial Points and the $\mathbb{M}$ 4.8^{+} Events Nearby

d= distance between any two adjacent spatial points measured along the arc

R= radius of the SCAE

de= the distance measured along the circular arc between a spatial point and the nearest $\mathbb{M}$ 4.8^{+} event

re= the distance between the center of the circular arc and the nearest $\mathbb{M}$ 4.8^{+} event



○ spatial point

* $M4.8^{+}$event

Among the 5^{+} de values, 1 of them can be quite large (≤0.5d), 1 of them can be moderate small (≤0.3d), and the rest of them must be small(≤0.1d). All the 5 values of re must be close to the value of R ($|re-R|<0.05R$).

(or $|re-R|<0.05d$ for a SLE)

- A SCAE with N spatial point (N≧5):
  - the de value of one spatial point satisfies the inequality that de<0.3d
  - the de value of one spatial point satisfies the inequality that de<0.5d
  - The de value of every one of the other N-2 points satisfies the inequality that de<0.1d
  - The re value of the nearest event of each spatial point satisfies the inequality that |re-R|<0.05R (or |re-R|<0.05d for a SLE)
  - The concrete values stated above are obtained by the working experience our analysis. They might be modified slightly in the future.

Strong Line of Earthquakes (SLE)

- 5^+ uniformly distributed spatial points along a line (50km<length<500km)

- Near to each spatial point there is at least one event with M 4.8^+ occurred in the last 5 years (could be modified to 3 or 4 years in future, after more precise studies have been carried out)

- The occurrence time of the fifth spatial point with at least one M 4.8^+event nearby is called the confirming time of the strong line of earthquakes (SLE)

Secondary Strong Circular Arc of Earthquakes (SSCAE)

- 5^+ uniformly distributed spatial points along a horizontal circular arc (50km < length < 500km)
  - Near to each spatial point there is at least one event with M 4.6^+ and depth <50km occurred in 5 years (could be modified to 3 or 4 years in future, after more precise studies have been carried out)
  - The occurrence time of the fifth spatial point with at least one M 4.6^+ event nearby is called the confirming time of the strong circular arc of earthquakes (SCAE)

Secondary Strong Line of Earthquakes (SSLE)

- 5^+ uniformly distributed spatial points along a line (50km<length<500km)

- Near to each spatial point there is at least one event with M 4.6^+ occurred in the last 5 years (could be modified to 3 or 4 years in future, after more precise studies have been carried out)

- The occurrence time of the fifth spatial point with at least one M 4.6^+ event nearby is called the confirming time of the strong line of earthquakes (SLE)

Hin-Chi Lei and Chi-Wang Tang, **Circular Arcs and Curvilinear Distributions of Events of Earthquakes in Taiwan ,** The Thirteenth National Conference on Structural Engineering/ The Third National Conference on Earthquake Engineerin, Taoyuan, Taiwan, 24-26 August, 2016 (Paper No. 1113).

中華民國第十三屆結構工程研討會暨第三屆地震工程研討會
The Thirteenth National Conference on Structural Engineering/
The Third National Conference on Earthquake Engineering
Taoyuan, Taiwan, 24-26 August, 2016
Paper No. 1113

台灣地震圓弧與地震曲線之研究

Circular Arcs and Curvilinear Distributions of Events of Earthquakes in Taiwan

Hin-Chi Lei [1] Chi-Wang Tang [2]

[1] 中央大學土木工程學系教授 E-mail: hinchili@cc.ncu.edu.tw, (0913877583)
[2] 中央大學土木工程學系研究生

摘要

中華民國第十三屆結構工程研討會暨第三屆地震工程研討會
The Thirteenth National Conference on Structural Engineering/
The Third National Conference on Earthquake Engineering
Taoyuan, Taiwan, 24-26 August, 2016
Paper No.: 1113

台灣地震圓弧與地震曲線之研究

Circular Arcs and Curvilinear Distributions of Events of Earthquakes in Taiwan

Hin-Chi Lei [1] Chi-Wang Tang [2]

[1] 中央大學土木工程學系教授 E-mail: hinchili@cc.ncu.edu.tw (0913877583).
[2] 中央大學土木工程學系研究生.

摘要

根據破壞力學的分析，我們發現地震的分布型態對於了解地殼的破損十分重要。例如 n 個排列成圓弧的 5 級地震，對地殼的損壞比 n 個隨機排列的 5 級地震來的大很多。此觀點被地震弧和地震鏈的地震前兆分析所證實。

我們發現在過去 42 年，發生在台灣本島成沿海的 14 個地震圓弧中有七成在見現後 6 個月內在弧的附近有大於 5.8 的強震。另外，我們也發現，地震鏈也是預測強震的重要訊號。在過去發生在台灣本島成沿海 64 個強震中，有高達七成五的強震(48 個)，在其發生的前半年內經線震央的一定範圍皆出現強地震鏈。

在集集大地震前我們既發現異常的地震弧也發現異常的強地震鏈。此地震弧和強地震鏈皆出現在台灣本島南部。

關鍵字：集集大地震、地震圓弧、地震鏈.

Abstract

Motivated by fracture mechanics, it is found that when analyzing the damages of the crust caused by the earthquakes, not only the magnitudes, but also the *distribution patterns* of the earthquakes should be considered. For example, the damage to the crust caused by a circular arc of n earthquakes of magnitude 5 should be much larger than that by a set of n randomly distributed events with the same magnitude. This viewpoint is supported by our investigations of the circular arcs and vertical chains of earthquakes as the precursors of strong earthquakes.

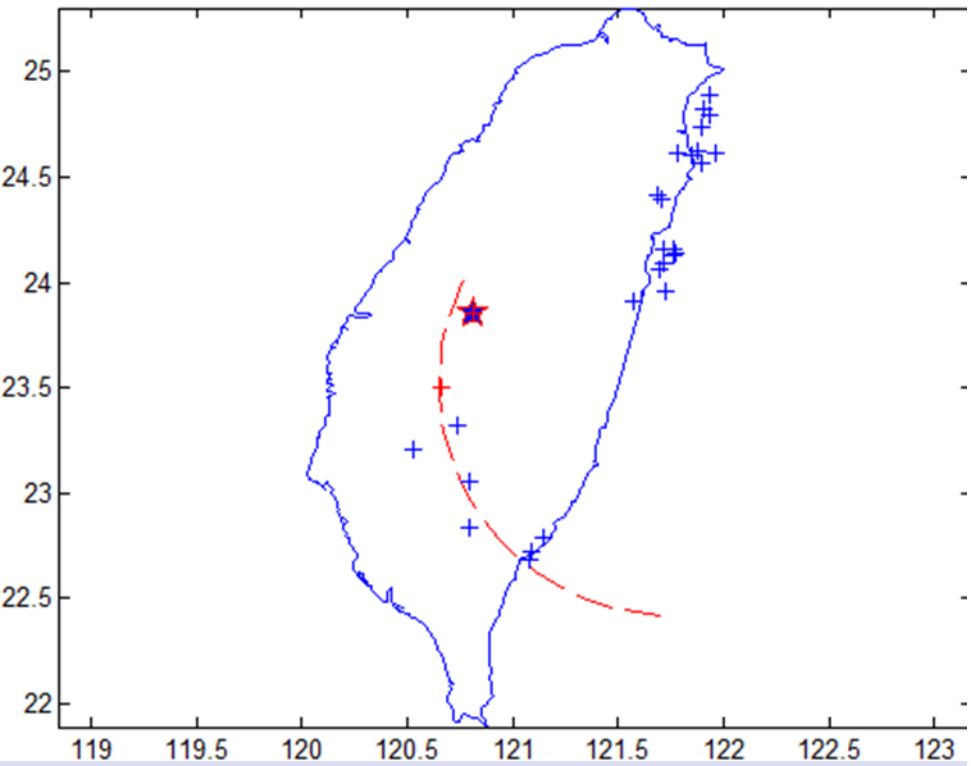
First, many circular arcs of earthquakes have been found in Taiwan over the past 42 years. For the arcs we have studied [2], after the appearances of about 70% of them strong events with M≧5.8 occurred close to the arcs within 6 months. Second, the linear distribution of earthquakes in the vertical direction of the crust, i.e., the vertical chain of earthquakes, is also important in predicting strong earthquakes. For 75% of the 64 strong earthquakes over 5.7 in the past, strong vertical chains occurred in certain distances from the main shocks within 6 months before the occurrences of the shocks [3]. In certain special regions, the appearances of the strong vertical chains can provide us information about sequential strong earthquakes or strong vertical chains [3].

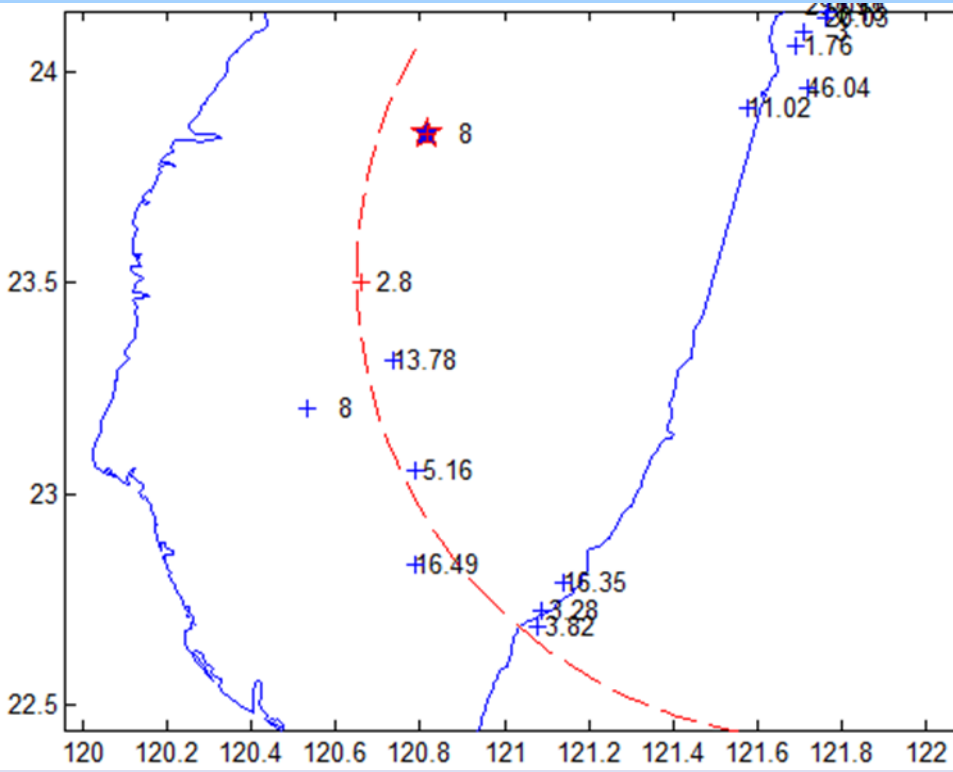
One of the remarkable arcs is that formed before the Chi-Chi earthquake in Taiwan. About a bit more than two years before that disaster there was a circular arc of events with M≧4.8 developed gradually in the southern part of Taiwan. The vertical chains of earthquakes before the Chi-Chi earthquakes are also remarkable. A bit more than one year before the Chi-Chi earthquake there was a vertical chain of earthquakes with the length over 12 km developed in the shallow crust about 40 km away from the center of the main shock of the Chi-Chi earthquake. There were more than 200 events happened along this chain in 24 hours. The occurrences of them show us of the information and the locations of the energy localization in the crust.

Keywords: Chi-Chi earthquake, circular arc of earthquakes, vertical chain of earthquakes

NCUCE

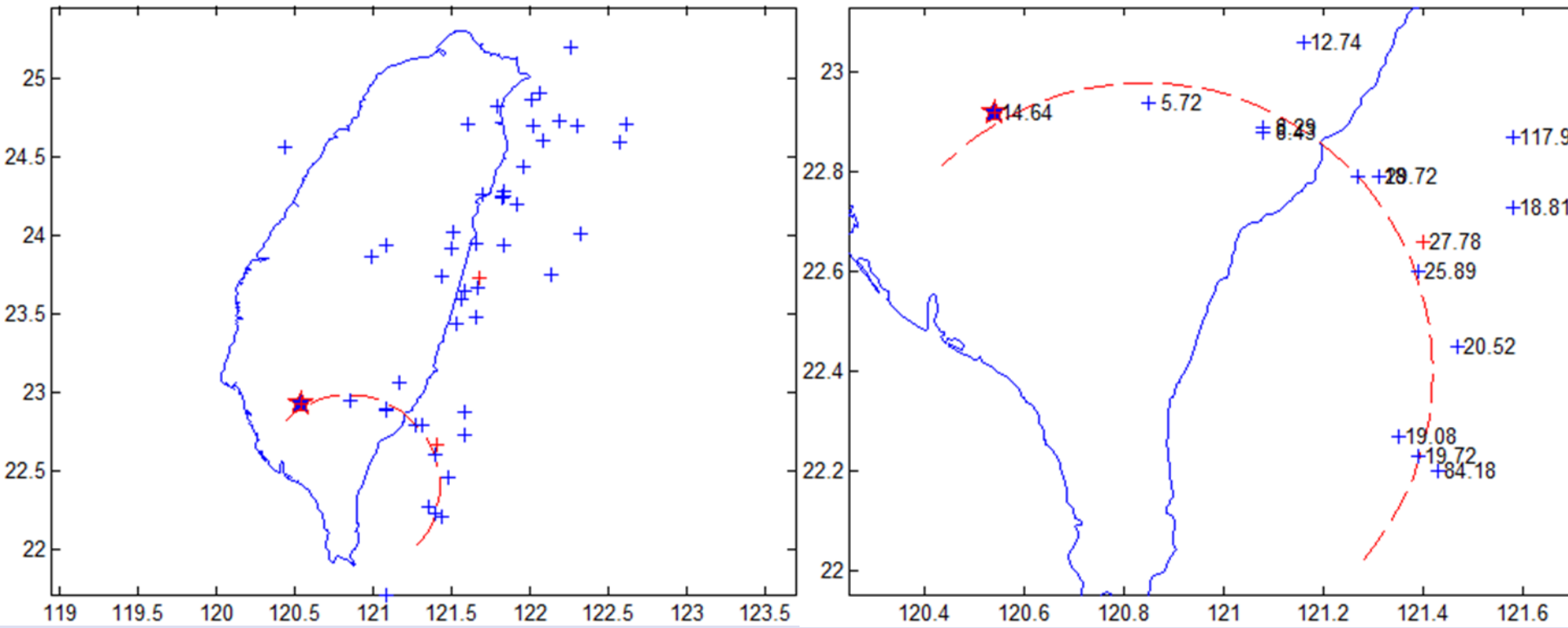
9 號弧





1999/9/20 17:47:15.85 8(km) M7.3

14 號弧



2016/2/5 19:57:26 14.64(km) M6.6

5. Intersections of Arcs and Other Distribution Patterns of Earthquakes

We have also found some intersecting SCAE. One of them is reported in the following tables.

Table 11. The intersection of two SCAE around 2011 to 2013

N	x	y	Y	M	D	Z(km)	M	location of the arc
1	121.5900	23.5900	2011	6	10	34.87	5.07	
2	121.5200	23.5100	2011	7	12	31.23	5.28	
3	121.6200	23.8000	2011	8	11	32.38	4.82	
4	121.4800	23.3800	2012	8	17	26.00	5.2	
⑤	121.5800	23.9800	2012	12	2	11.79	5.02	
6	121.4600	24.3000	2013	3	7	5.55	5.87	
1	121.5500	24.0100	2011	7	19	14.16	4.81	
2	121.6700	23.9100	2012	6	10	39.59	4.8	
3	121.5800	23.9800	2012	12	2	11.79	5.02	
4	121.5600	23.9700	2012	12	2	11.75	4.83	
5	121.4600	24.3000	2013	3	7	5.55	5.87	
main shock		2013/3/7	3:36:45	5.55(km)	M5.87			

Furthermore, other linear and curvilinear distributions of earthquakes might be significant too. For example, we have found some parabolic arcs of earthquakes which are related to some strong events.

In addition to the above patterns of distributions of earthquakes in the *tangential* directions on the crust, one of us (H.C. Lei) and P.Y. Chen are also investigating the *linear* distributions of earthquakes in the *vertical* direction of the crust [3]. A new concept, the strong vertical chain of earthquakes (abbreviated as SVCE) is proposed. A bit more than one year before the Chi-Chi earthquake there was a vertical chain of earthquakes with the length over 12 km developed in the shallow crust about 40 km

away from the center of the main shock of the Chi-Chi earthquake. The chain was developed about one day around July 17 and 18 in 1998. As can be seen in Figure 4, there were more than 200 events happened along this chain about 24 hours. The center line is located at (120.65, 23.5). In the figure, the blue stars denote the events along the vertical chain of earthquakes while the red star stands for the main shock of the Chi-Chi earthquake.

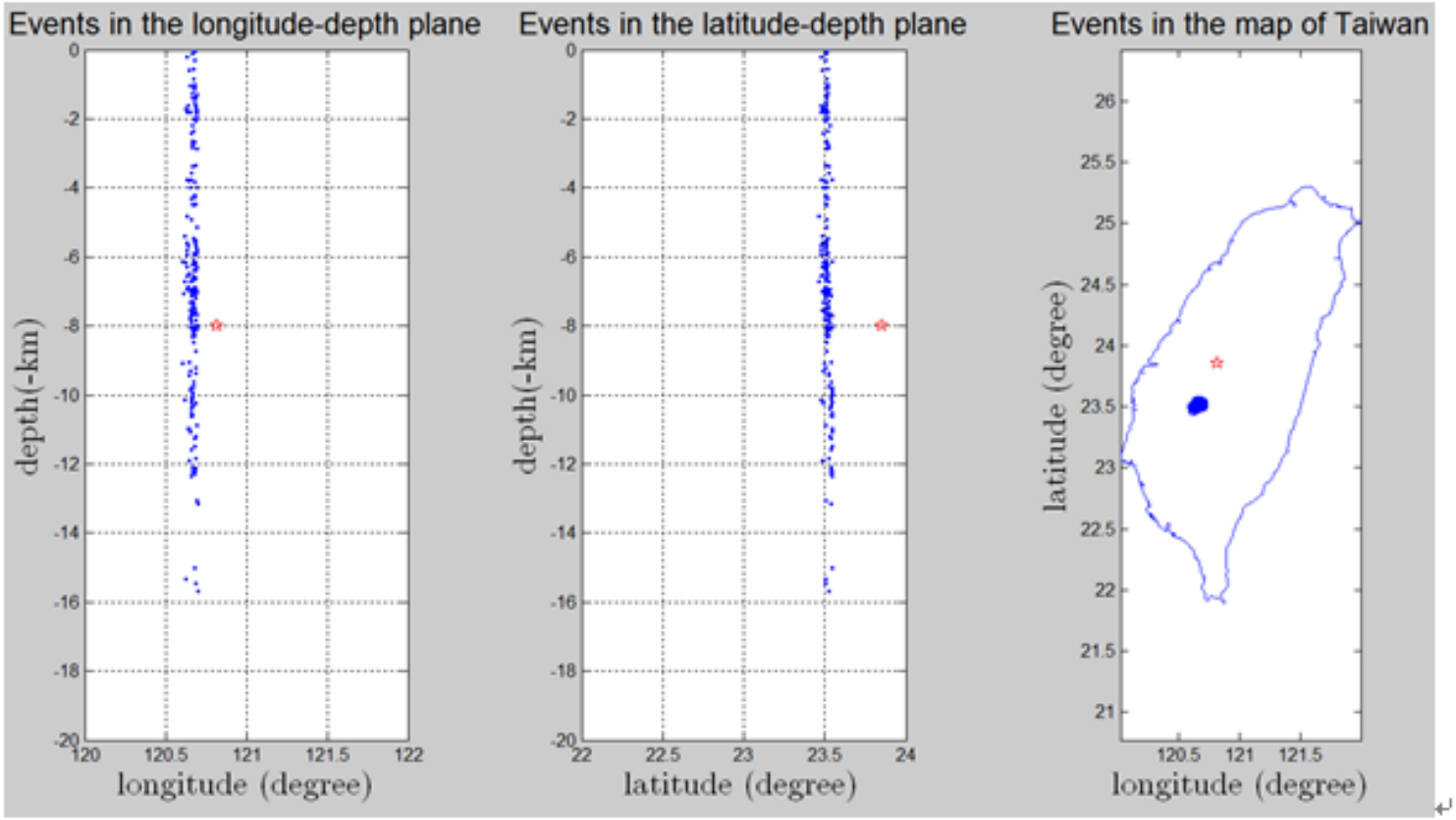


Figure 4. The vertical chain of earthquakes occurred around July 17th and 18th in 1998

Moreover, on June 10 in 1999, July 7 in 1999, August 29 in 1999, and September 20 in 1999 there were other four shorter vertical chains of earthquakes developed along the long vertical chain of

2. 唐基望(Chi-Wang Tang)，「台灣地震圓弧之研究」(The Circular Arcs of Earthquakes in Taiwan) (Master Thesis supervised by Hin-Chi Lei)。碩士論文，國立中央大學土木工程研究所，中壢 (2016)。

3. 陳姵妤(Pei-Yu Chen)，「台灣地震鏈的研究」(The Vertical Chains of Earthquakes in Taiwan) (Master Thesis supervised by Hin-Chi Lei)。碩士論文，國立中央大學土木工程研究所，中壢 (2016)。

Acknowledgement

The helpful discussion with P.Y. Chen is deeply appreciated.

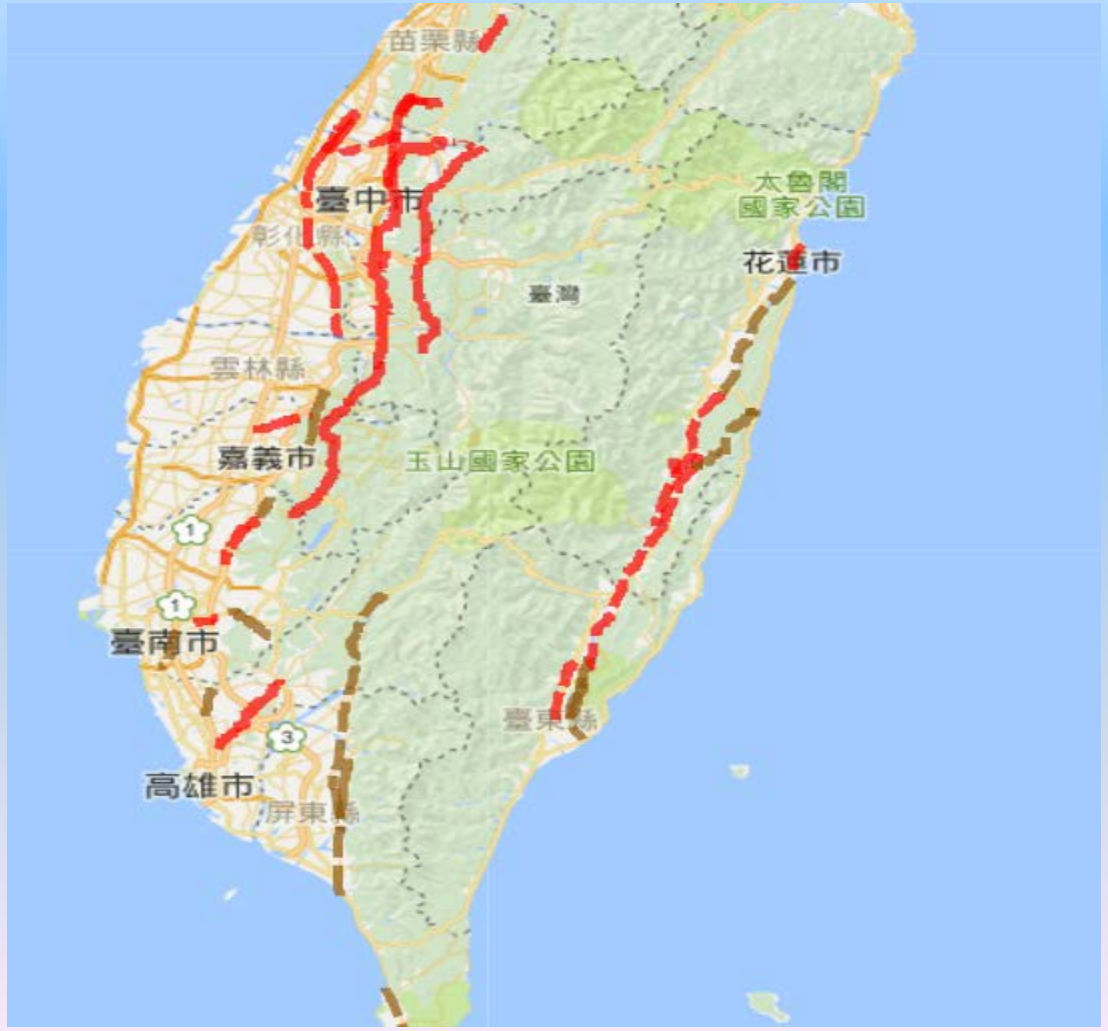
Conclusions of the 2016 08 paper by Hin-Chi Lei and Chi-Wang Tang

14 circular arcs of earthquakes have been found in Taiwan over the past 42 years. For the 14 arcs we have studied , after the appearances of 70% of them strong events with $M \geqq 5.8$ occurred close to the arcs within 6 months.

(About 10 arcs are found related to the strong events nearby, while 4 arcs are found irrelavant to any strong events)

Active Faults of Taiwan

The SCAE, SSCAE, SLE, SSLE we have found do not occur along the active faults of Taiwan




N
E
S
W
山腳斷層
南崁斷層
湖口斷層
新城斷層
斗煥坪斷層
大茅埔-雙冬斷層
車籠埔斷層
屯子腳斷層
彰化斷層
梅山斷層
大尖山-觸口斷層
六甲斷層
六龜斷層
旗山斷層
潮州斷層
宜蘭、牛鬥斷層
四季、環山斷層
霧社斷層
海岸山脈斷層
中央山脈斷層
玉里斷層
鹿野斷層
5.8
6.3
6.8
5.8
6.8
6.2
6.0
6.6
5.7
6.4
5.5
主要餘震(ML>5.5,至1999/09/23日)
九二一地震地表破裂帶
臺灣地區活斷層
玉山國家公園範圍

NCUCE

4) Stress Interaction Indicator :

Intersections of SCAE, SSCAE, SLE and SSLE

Hin-Chi Lei, **Circles, Circular Arcs and Lines of Earthquakes Around Taiwan,** **The 40th National Conference on Theoretical and Applied Mechanics, Hsinchu, Taiwan, ROC, November 25-26, 2016**

Circles, Circular Arcs and Lines of Earthquakes Around Taiwan

Hin-Chi Lei*

Department of Civil Engineering, National Central University

*Corresponding Author: E-mail: hinchili@cc.ncu.edu.tw

Abstract

In a recent paper [1] the concepts of strong circular arcs and lines of earthquakes are proposed. Many examples of strong circular arcs of earthquakes were the last 43 years occurred near to some intersection points of strong circular arcs or strong lines of earthquakes with magnitudes over 4.6. These might be caused by the interactions of different stress

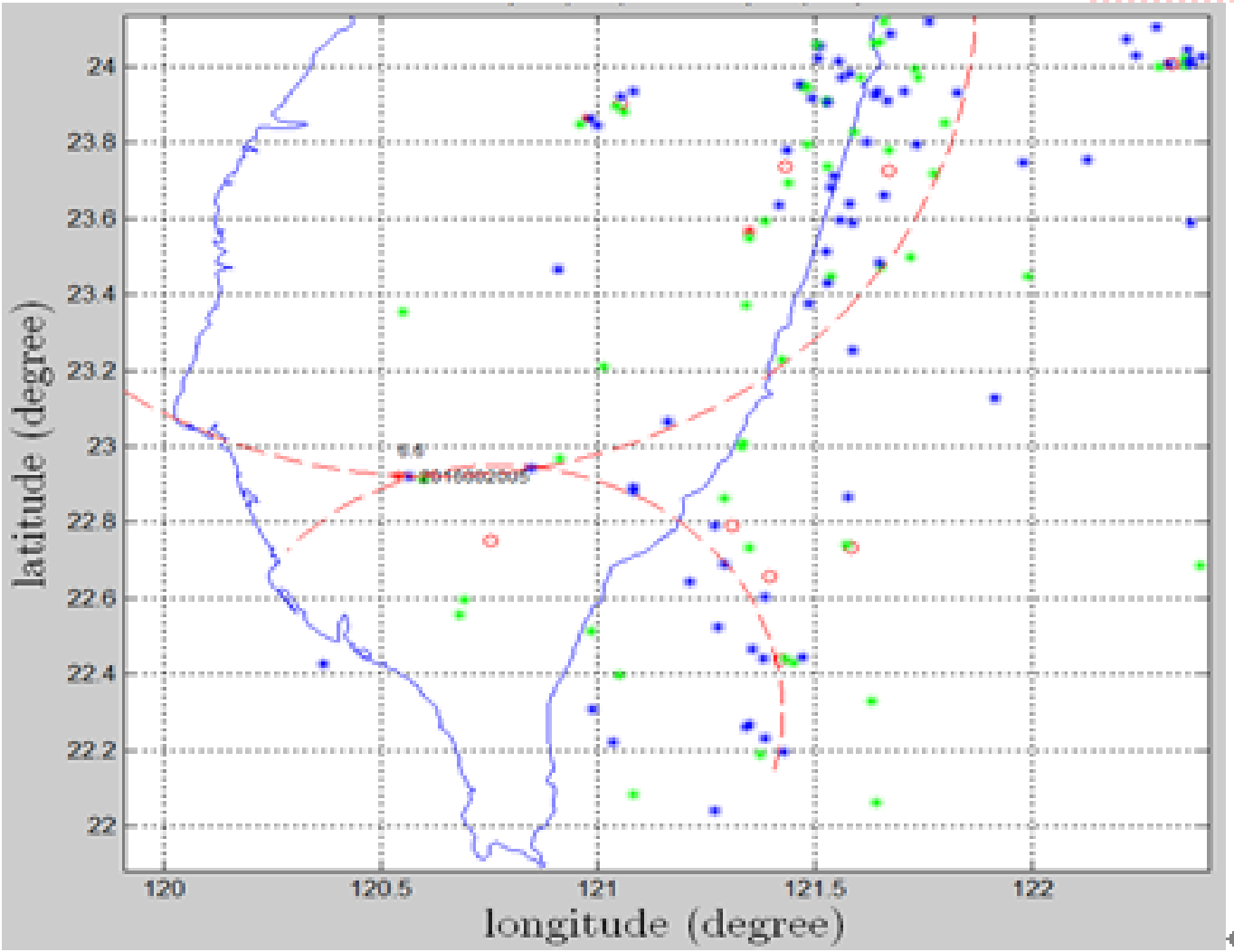


Fig. 32 An event with M=6.6 at one of the two intersection points of two SCAE. It is at the western ends of these two SCAE and occurred on 2016/2/6 in Kaohsiung.

Circles, Circular Arcs and Lines of Earthquakes Around Taiwan

Hin-Chi Lei*

Department of Civil Engineering, National Central University

*Corresponding Author: E-mail: hinchili@cc.ncu.edu.tw

Abstract

In a recent paper [1] the concepts of strong circular arcs and lines of earthquakes are proposed. Many examples of strong circular arcs of earthquakes were studied. It was found that they are important in the analysis of strong earthquakes. In this paper we provide more concrete examples and new ideas. First, it is found that, around Taiwan, most of the strong events with magnitudes over 5.8 in the last 43 years can be grouped into finite numbers of circles and lines. Second, in addition to the 14 arcs reported in [1, 2], much more new arcs and lines related to the strong earthquakes around Taiwan are reported in this article. In particular, it is found that almost all of the 59 strong earthquakes studied by us occurred around some intersection points of strong circular arcs or strong lines of earthquakes with M≧4.6. A three-step method is also proposed for the prediction of the future strong earthquakes.

Keywords: circular arc of earthquakes, line of earthquakes, circle of earthquakes

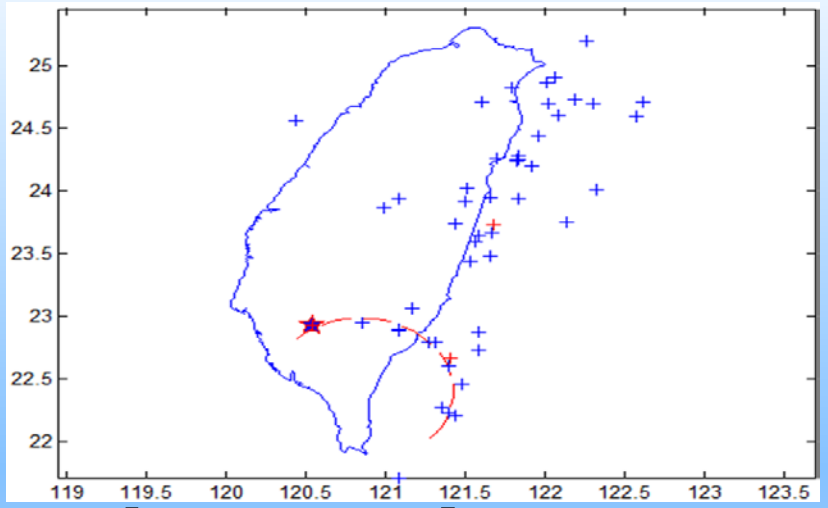
the last 43 years occurred near to some intersection points of strong circular arcs or strong lines of earthquakes with magnitudes over 4.6. These might be caused by the interactions of different stress concentration processes in different directions. The lines of earthquakes in this paper are horizontal while those in [1, 3] are vertical. A three-step method is also proposed for the prediction of the future strong earthquakes.

2. Fracture Mechanical Interpretation

In [1] we used an example from fracture mechanics to illustrate the importance of distribution pattern of earthquakes. Apart of the ideas in [1] is quoted below.

A row of 15 micro-voids in a tensile plate is shown in Fig. 1. If the width of the plate is w, the diameter of each of these micro-voids is 0.001*w, the thickness of the plate is b then the deducted area of the middle cross section is just 98.5% of the undamaged cross section area. This plate could be thought as nearly perfect if only the deducted area is considered. However, the plate is in fact

A SCAE (or SLE) can be treated as a stress localization indicator of the crust.



An intersection of 2^+ SCAE can be treated as a stress interaction indicator.

(Bi-axial, Triaxial, or Congugate Stress Effect or Others)

(SCAE+SCAE+SLE, SCAE+SLE, SLE+SLE, SCAE+SSCAE, etc.)

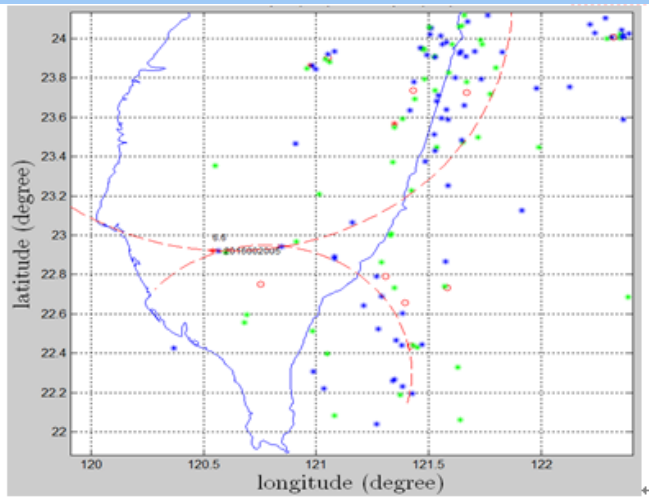
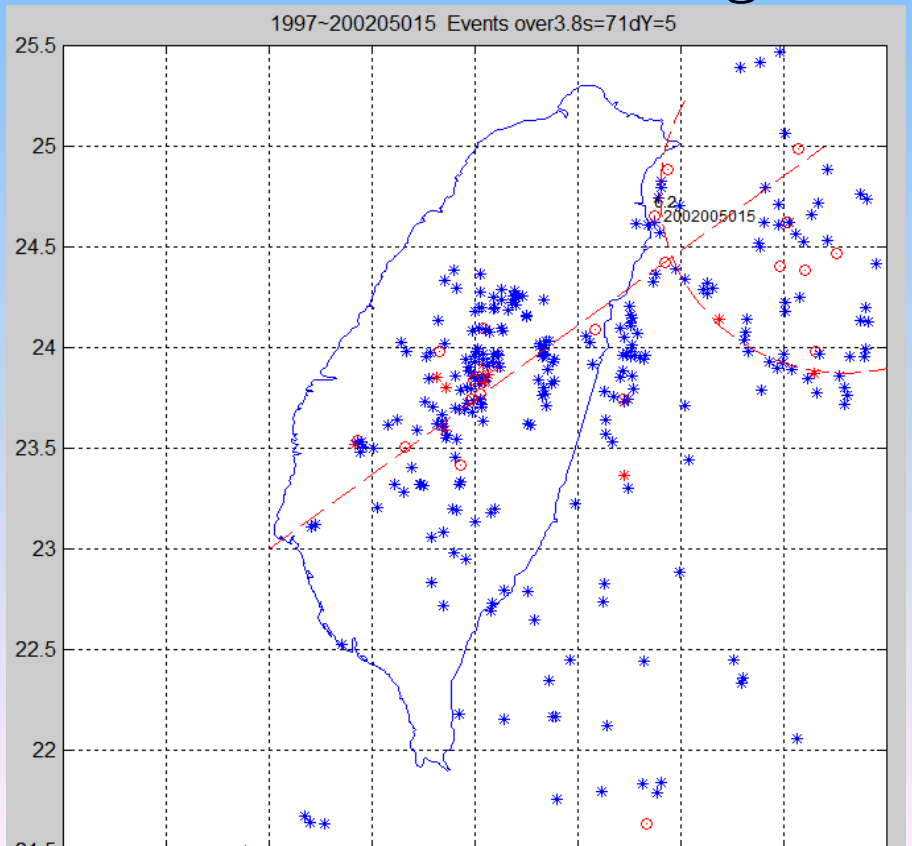


Fig. 32 An event with M=6.6 at one of the two intersection points of two SCAE. It is at the western ends of these two SCAE and occurred on 2016/2/6 in Kaohsiung.

In some years, there are many M4.6^{+} events on the map, then a lot of SCAE and SLE can be found. In such kind of situations the stress localization indicators and stress interaction indicators may provide us **too much** information. So we consider the events occurred 5 years before the main shock. If events in 10 years were considered the stress localization indicators and stress interaction indicators might make no sense.



M4.8^{+} events occurred 5years before a strong event of M 6.2 happen on May 15, 2002. It is probably that more than 2 SCAE or SLE can be found.

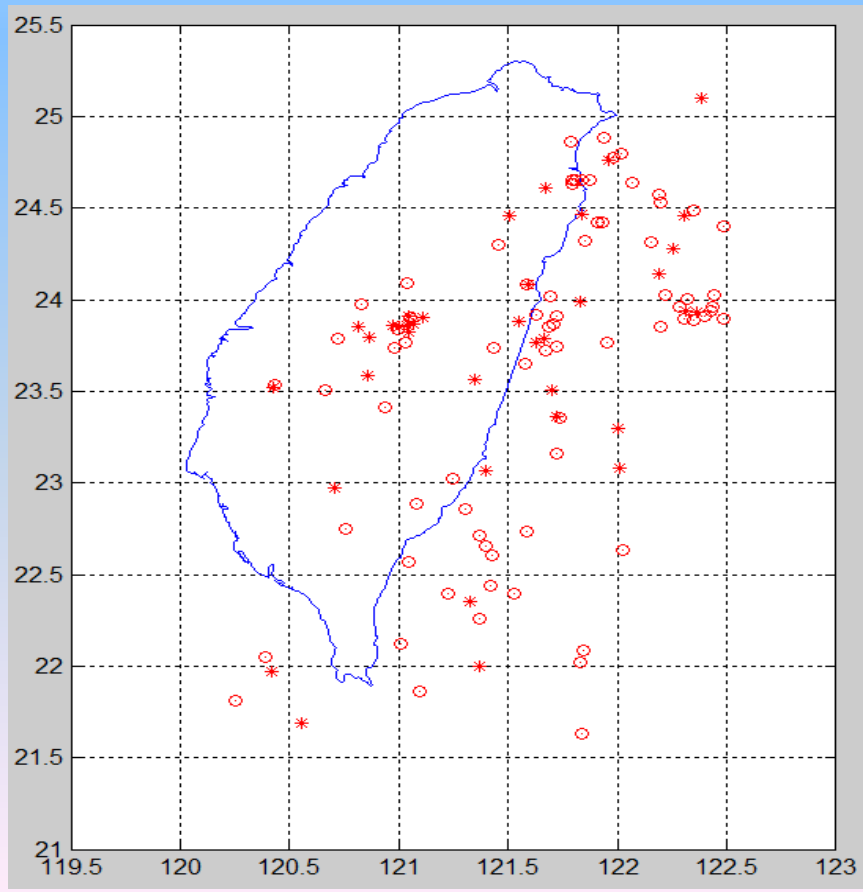
All the Strong Earthquakes around Taiwan over the last 40 years

1978 to 2016 Depth ≤50km

120˚ E to 122.5˚ E and 21.5˚ N to 25.5˚ N (around Taiwan)

13 Thirteen strong events after the Chi-Chi earthquake (from 1999/9/21 to 2000/6/9) are not considered

All of the **59 strong earthquakes (M≥5.99) are analyzed**



NCUCE

SE={SCAE, SSCAE, SLE, SSLE}

Every one of the 59 strong earthquakes occurred near to (within 70 km) one intersection point of two members of SE (within 3 years after the occurrence of the intersection point).

i.e., intersection points of strong circular arcs, strong lines of earthquakes, secondary strong circular arcs, secondary strong lines of earthquakes (with M≧4.8 or 4.6)

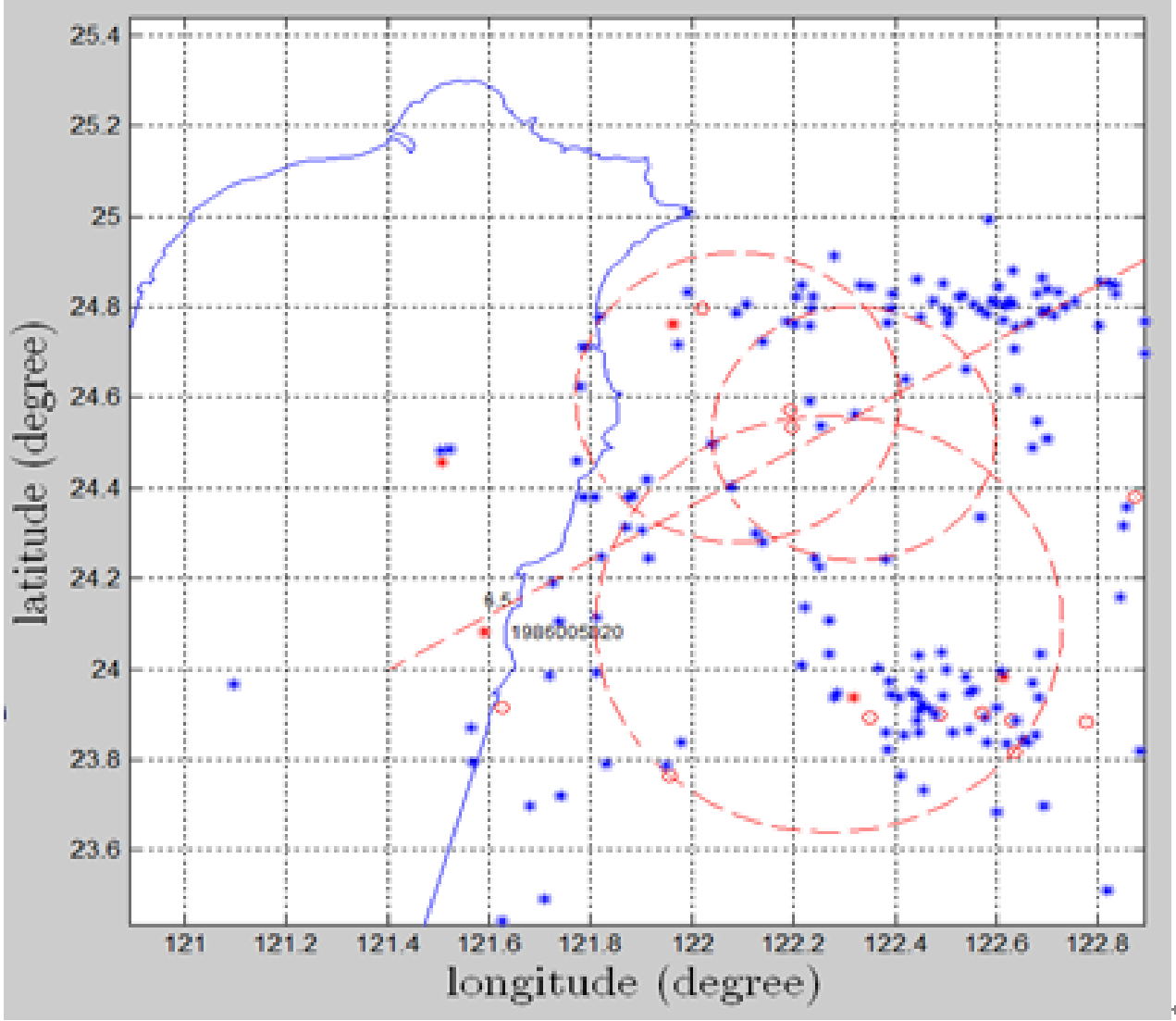


Fig. 6 An event with M=6.5 near the end of a SLE which cut through 3 intersecting SCAE. It occurred on 1986/5/20 along the coast of Hualien.

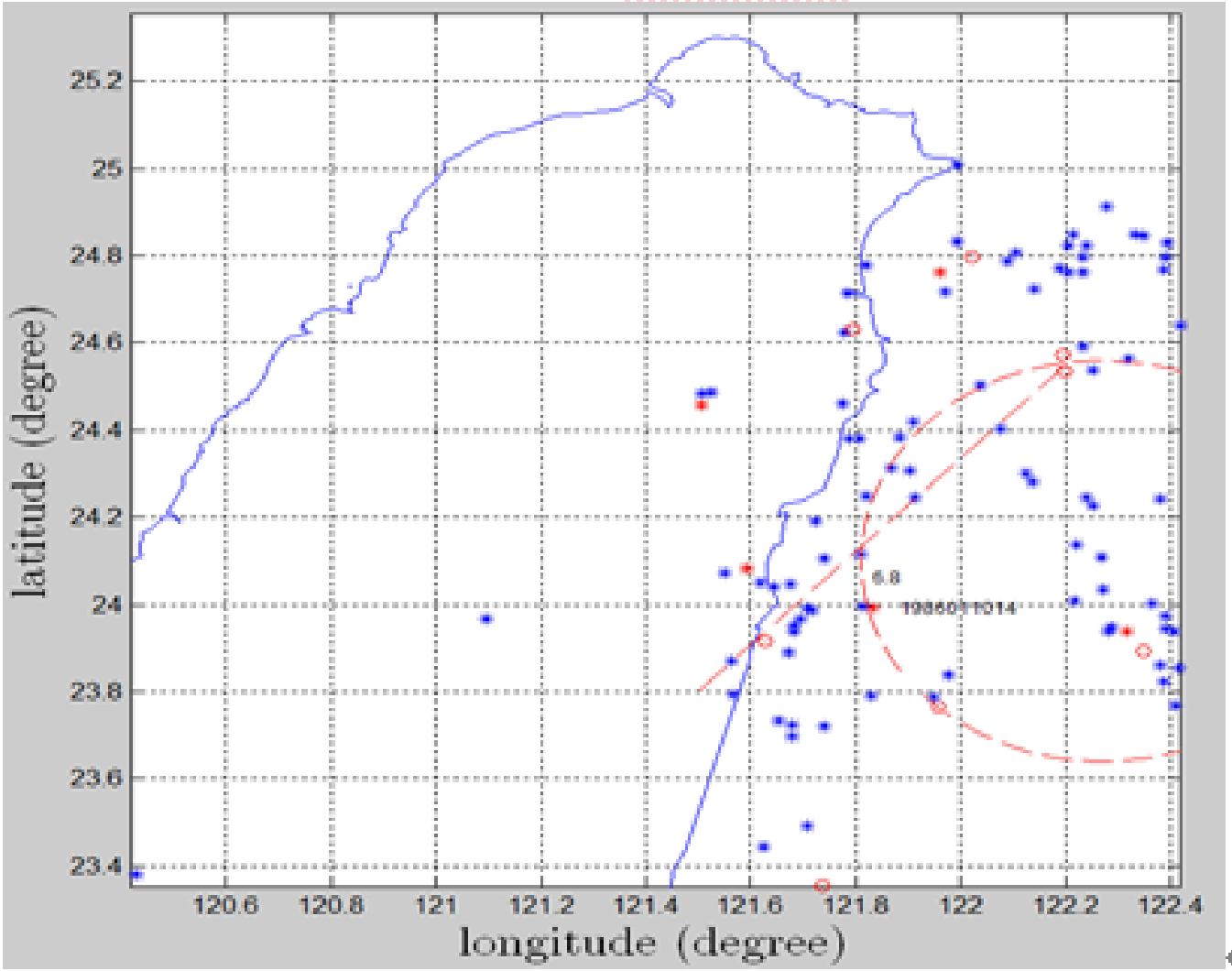


Fig. 7 An event with M=6.8 near the intersection point of a SLE and a SCAE. It is also embedded in the SCAE and occurred on 1986/11/14 in the sea area outside Hualien.

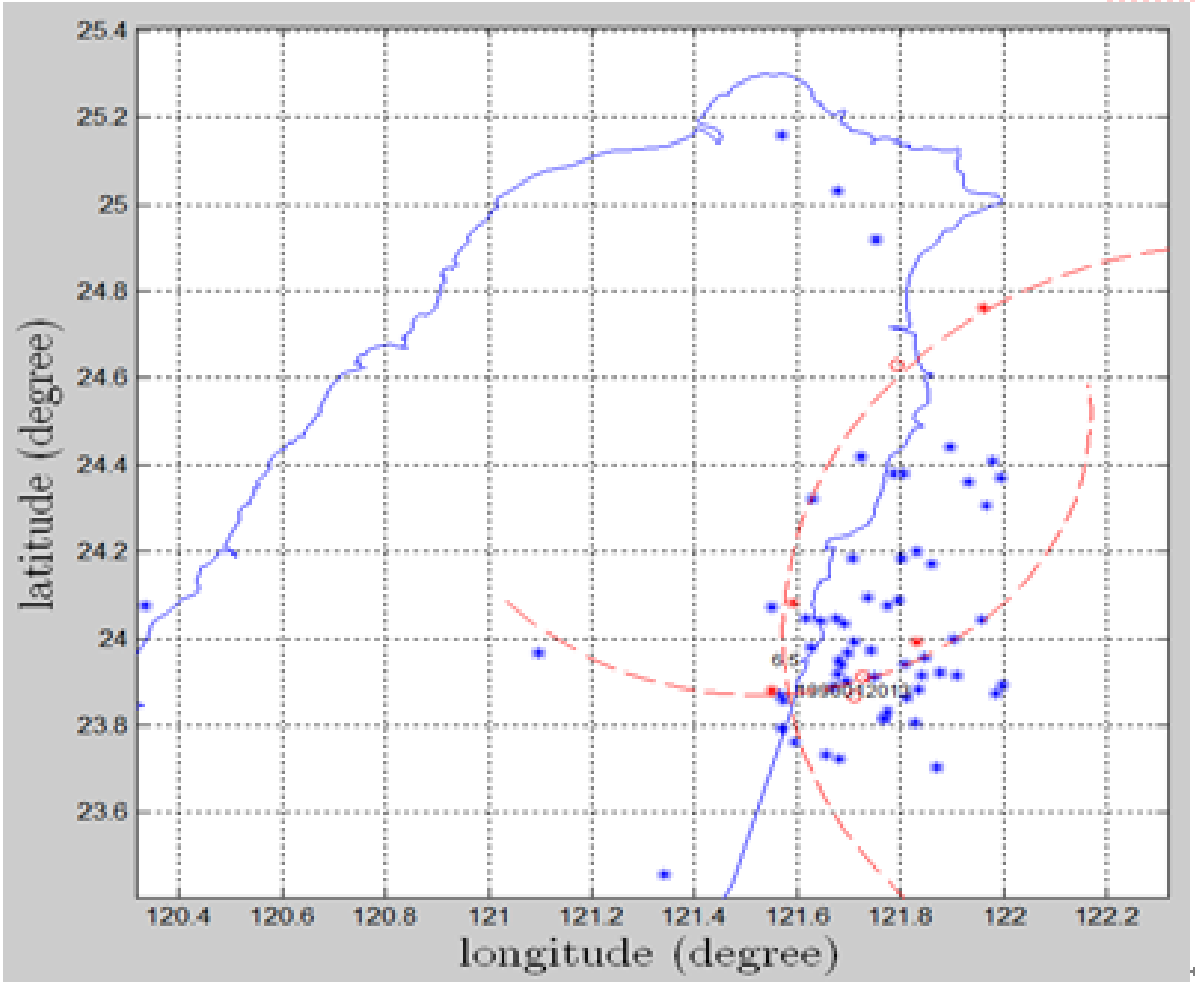


Fig. 8 An event with M=6.5 near the intersection point of two SCAE. It occurred on 1990/12/13 along the coast of Hualien.

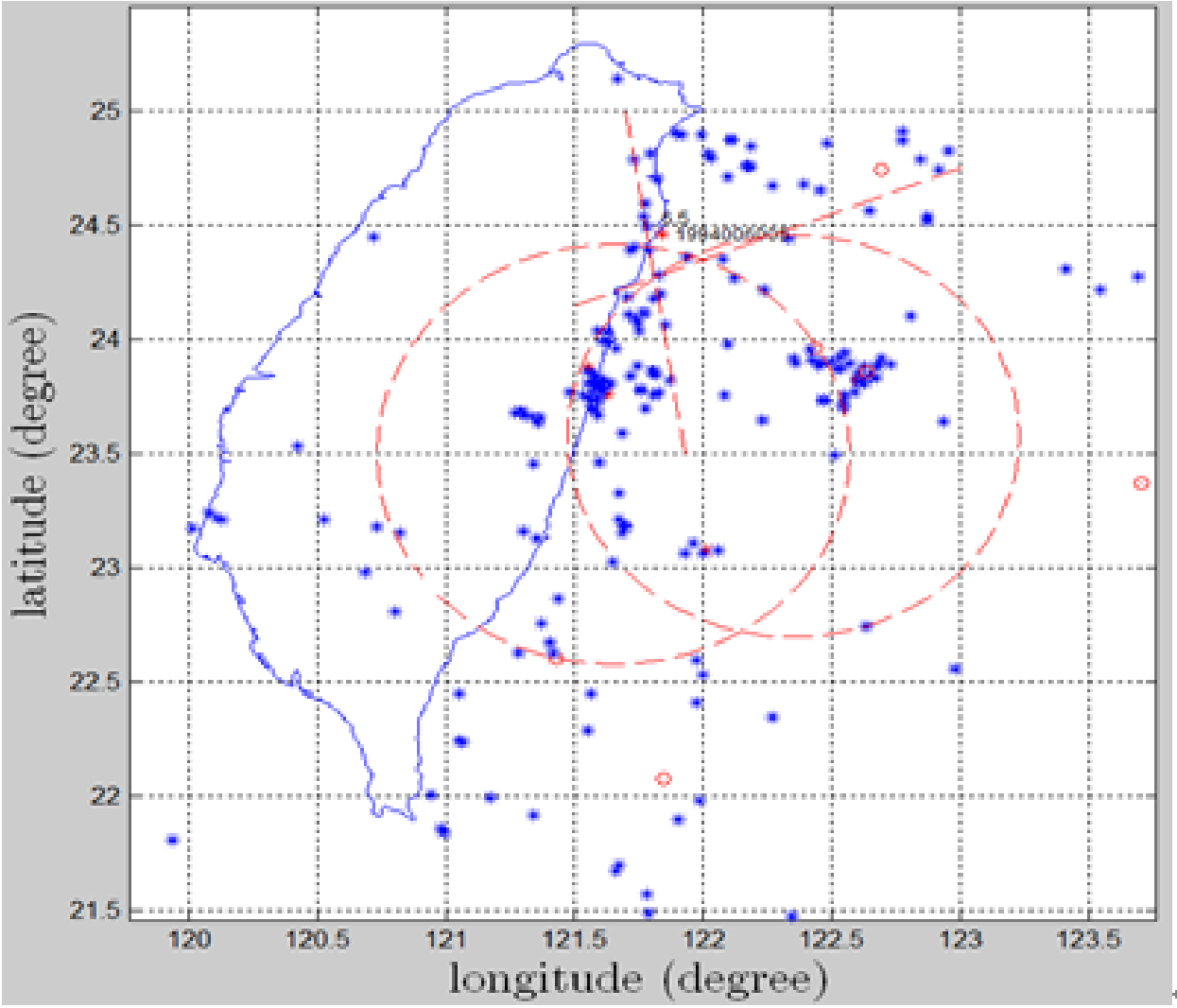


Fig. 9 An event with M=6.5 near the intersection point of two SLE and the one of two SCAE. It occurred on 1994/6/5 along the coast of Hualien.

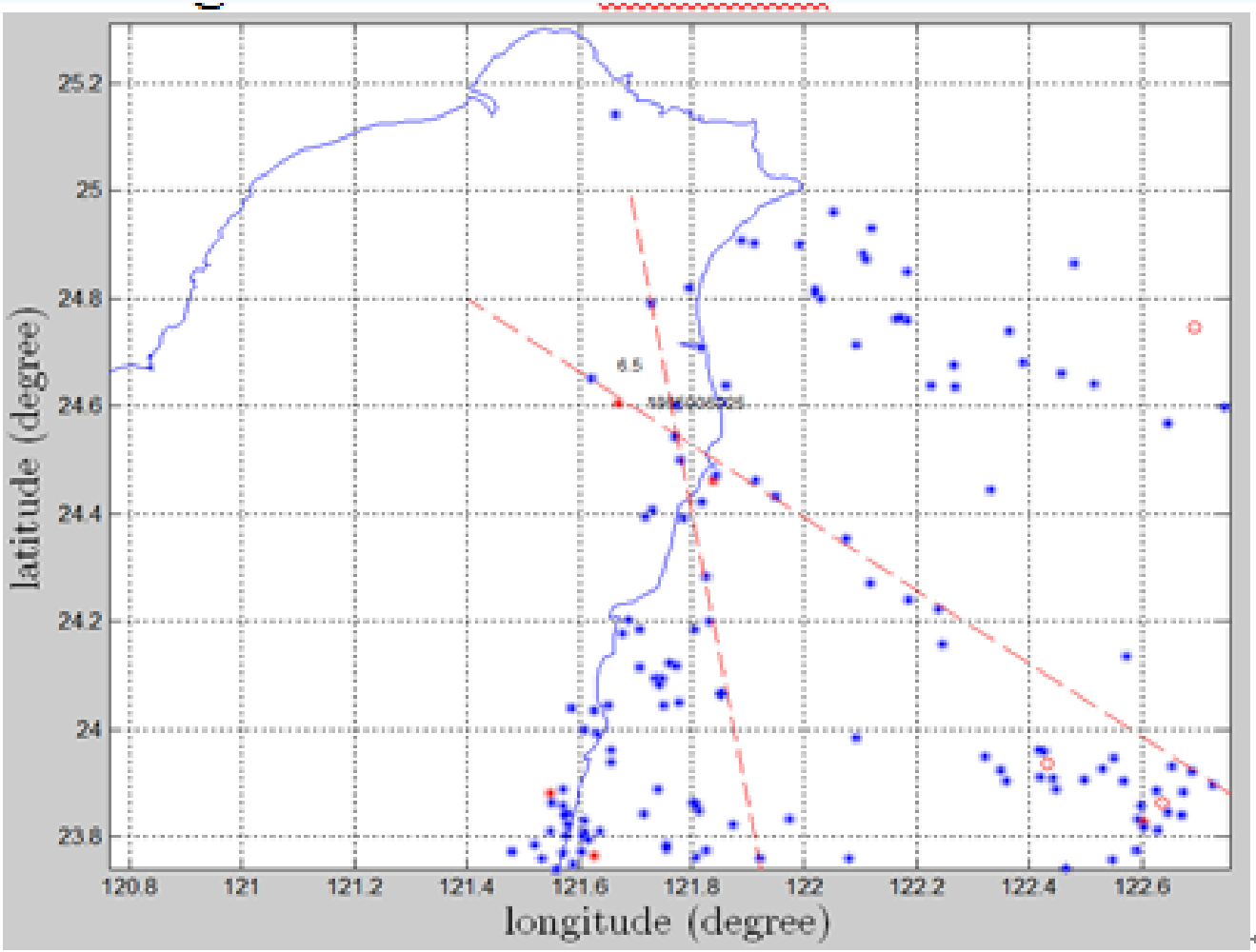


Fig. 10 An event with M=6.5 near the intersection point of two SLE. It is also embedded in one of the two SLE and occurred on 1995/6/25 in Yilan.

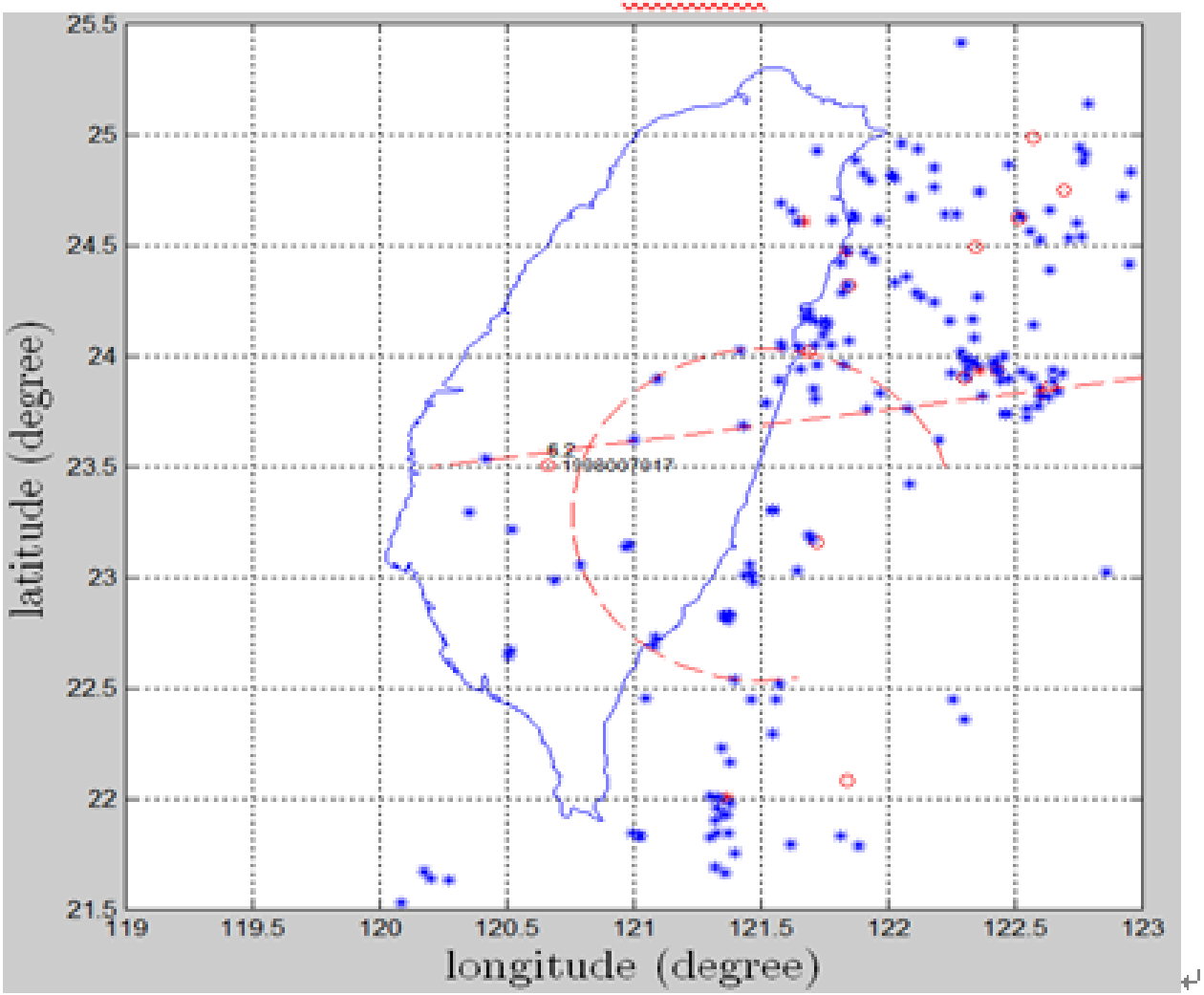


Fig. 11 An event with M=6.2 near the intersection point of a SLE and a SCAE. It occurred on 1998/7/17 near Chiayi and Nantou.

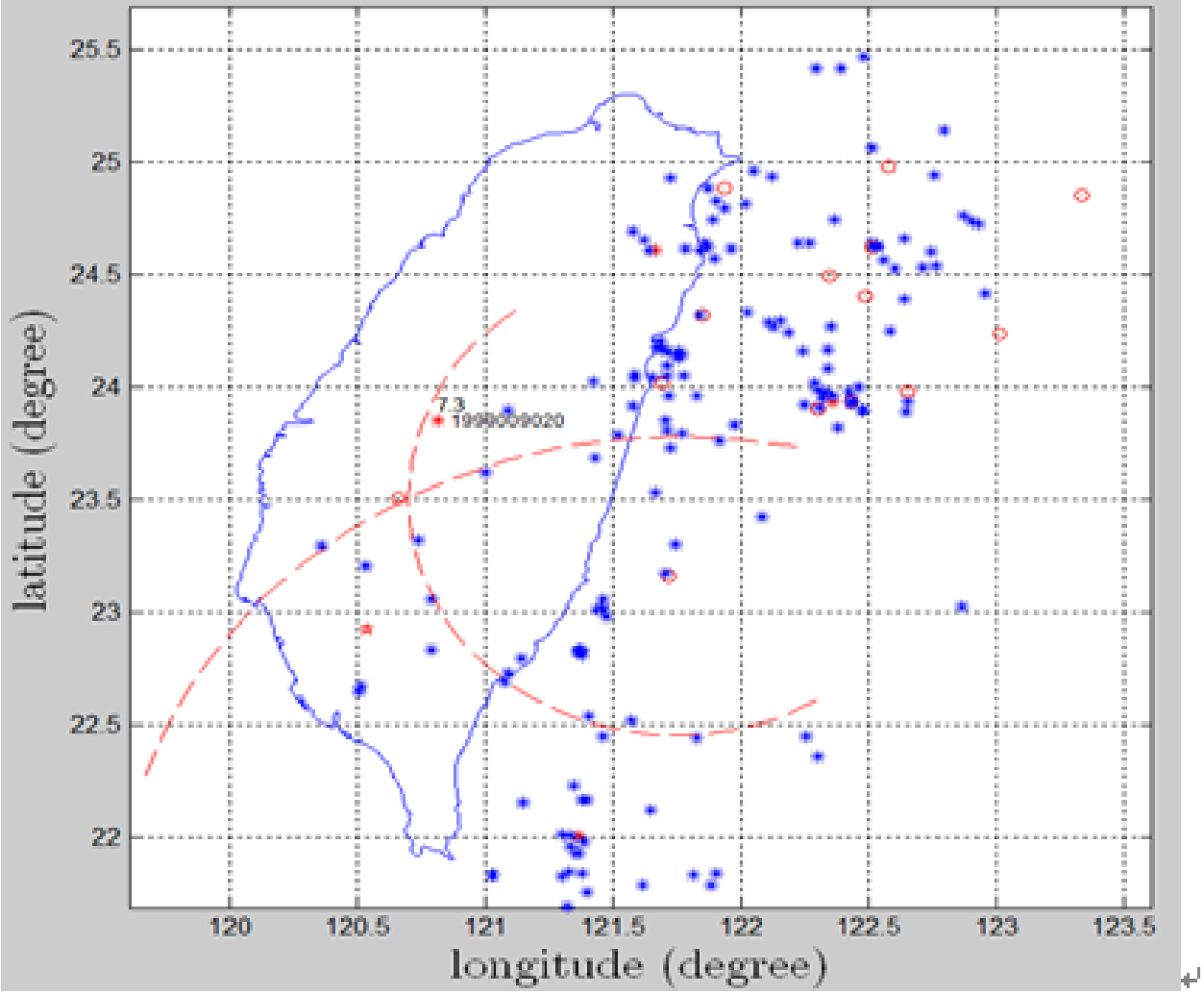


Fig. 12 An event with M=7.3 near the intersection point of two SCAE. It occurred on 1999/9/21 in Chi-Chi, Nantou.

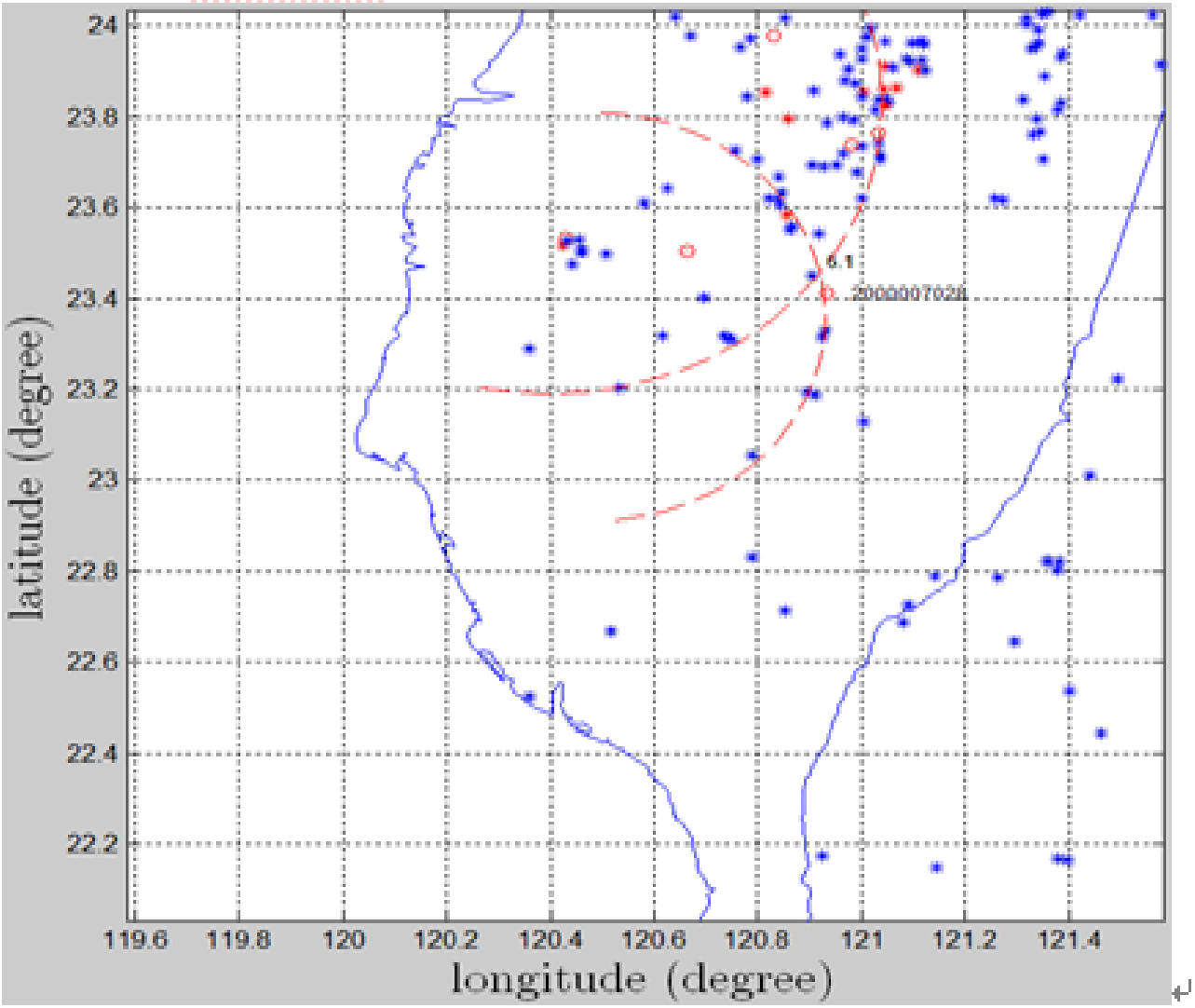


Fig. 14 An event with M=6.1 near the intersection point of two SCAE. It is embedded in one of the two SCAE and occurred on 2000/7/28 near Chaiyi and Nantou.

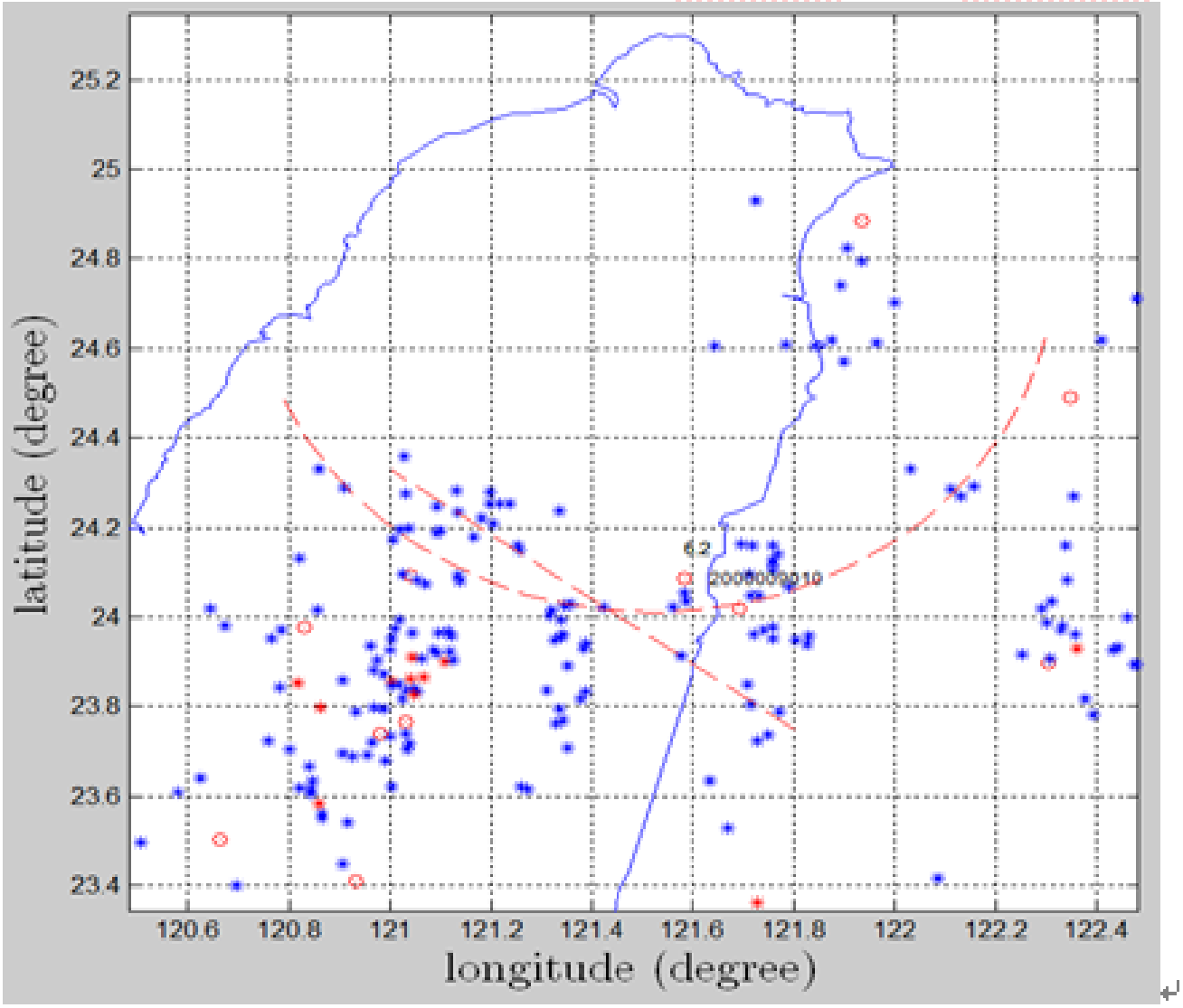


Fig. 15 An event with M=6.2 near the intersection point of a SCAE and a SLE. It occurred on 2000/9/10 along the coast of Hualien.

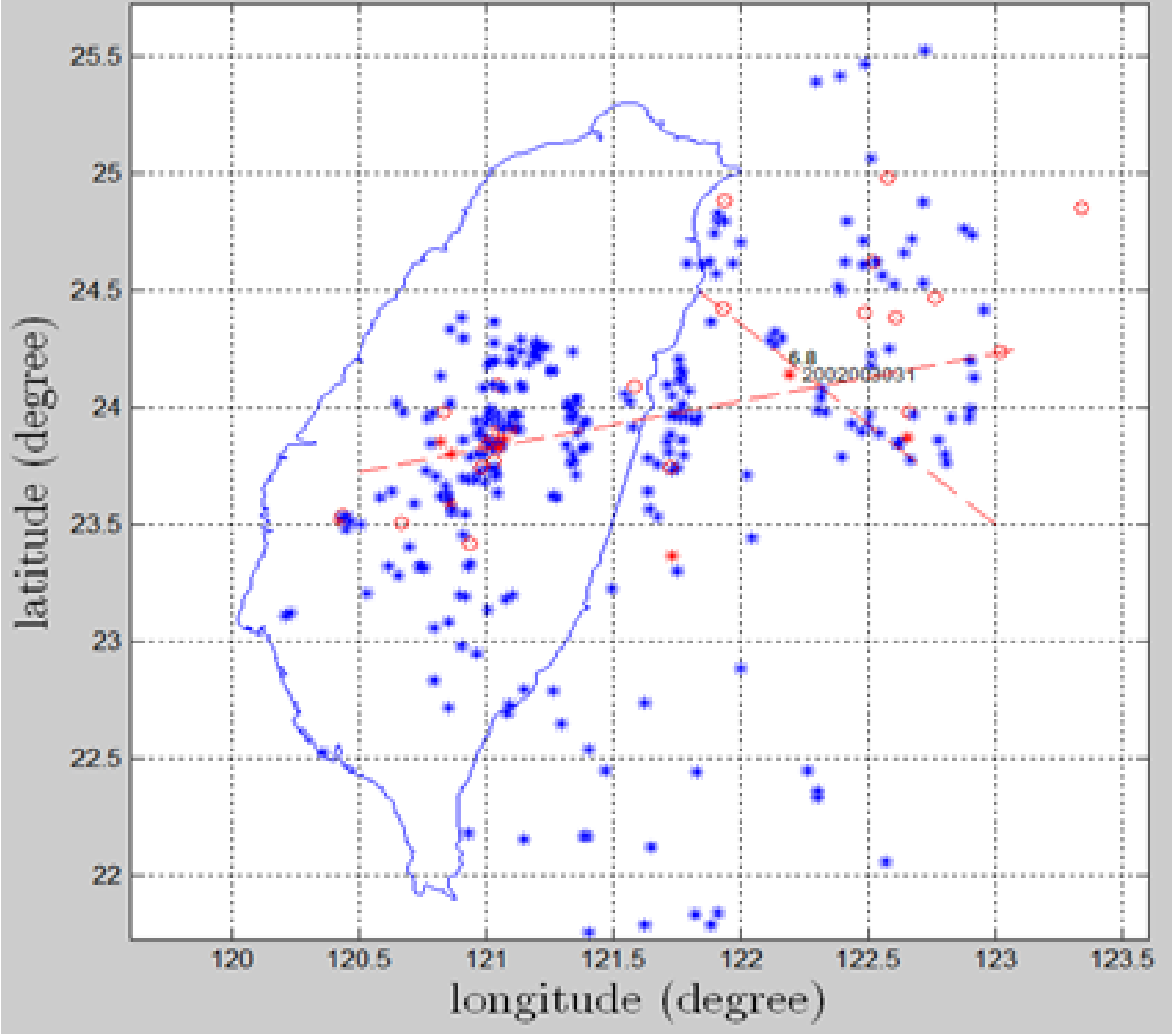


Fig. 16 An event with M=6.8 near the intersection point of two SLEE. It occurred on 2002/3/31 under the sea out of Hualien.

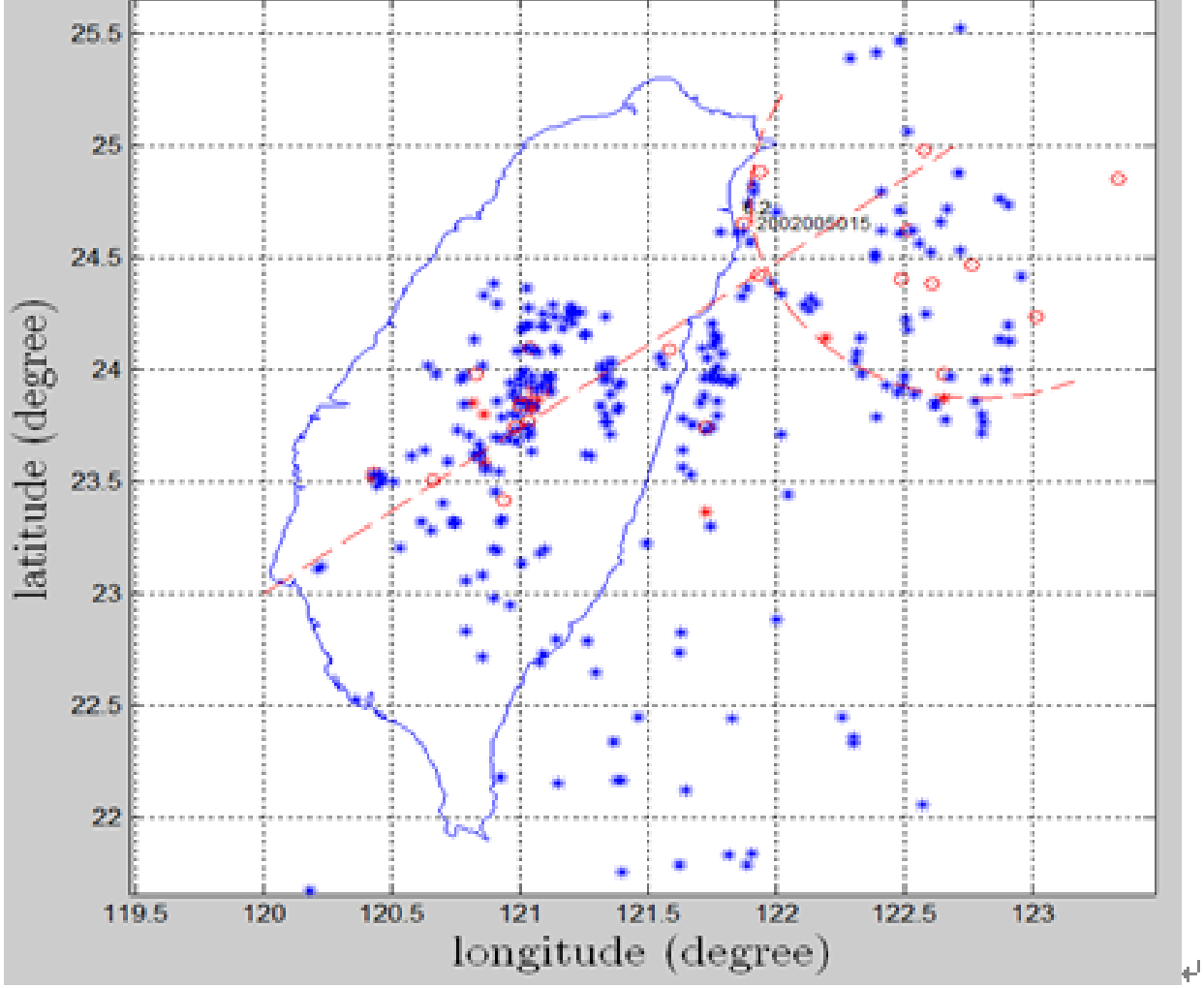


Fig. 17 An event with M=6.2 near the intersection point of a SLE and a SCAE. It is also embedded near the northern end of the SCAE and occurred on 2002/5/15 along the coast of Yilan.

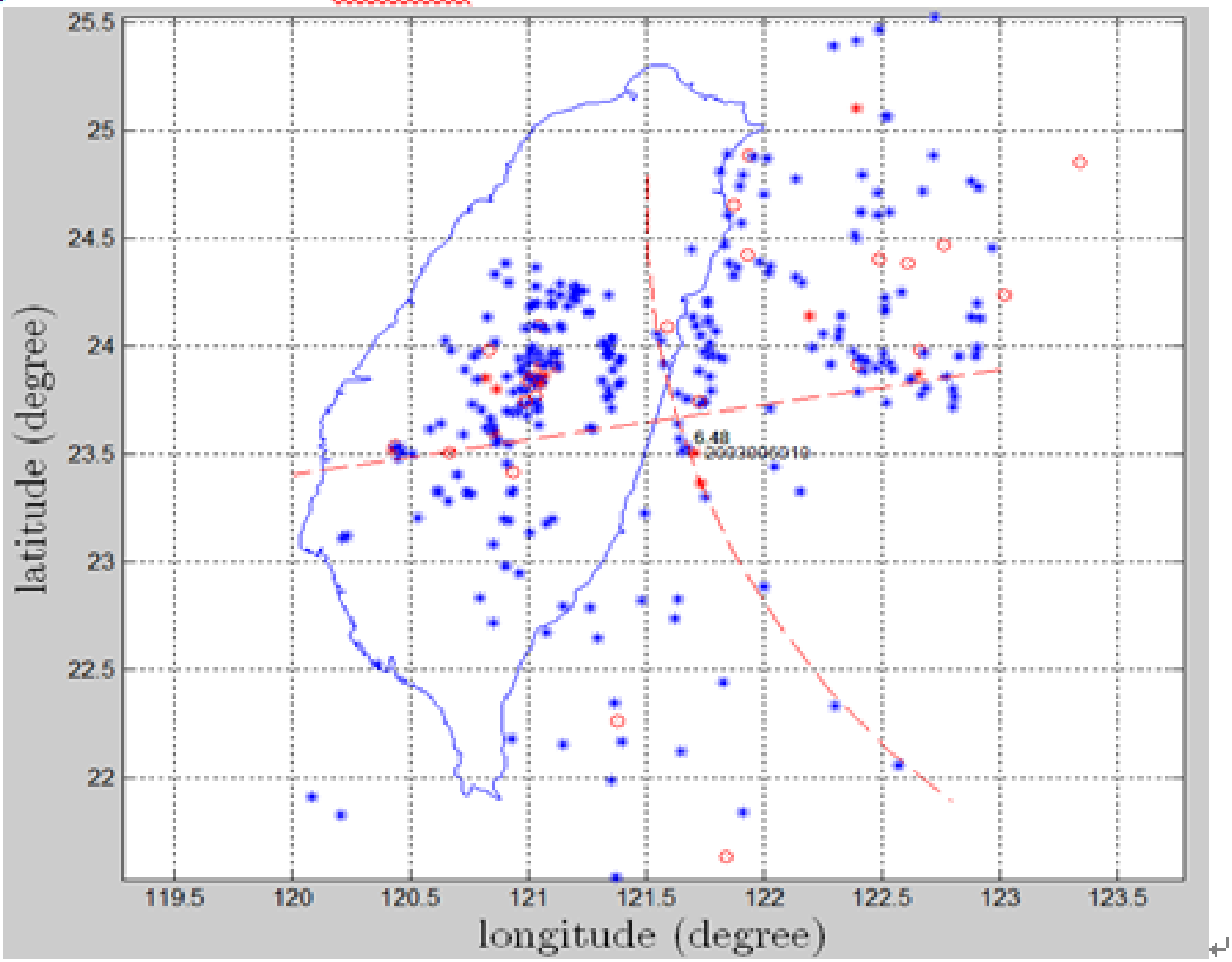


Fig. 18 An event with M=6.48 near the intersection point of a SLE and a SCAE. It is also embedded in the SCAE and occurred on 2003/6/10 under the sea outside Hualien.

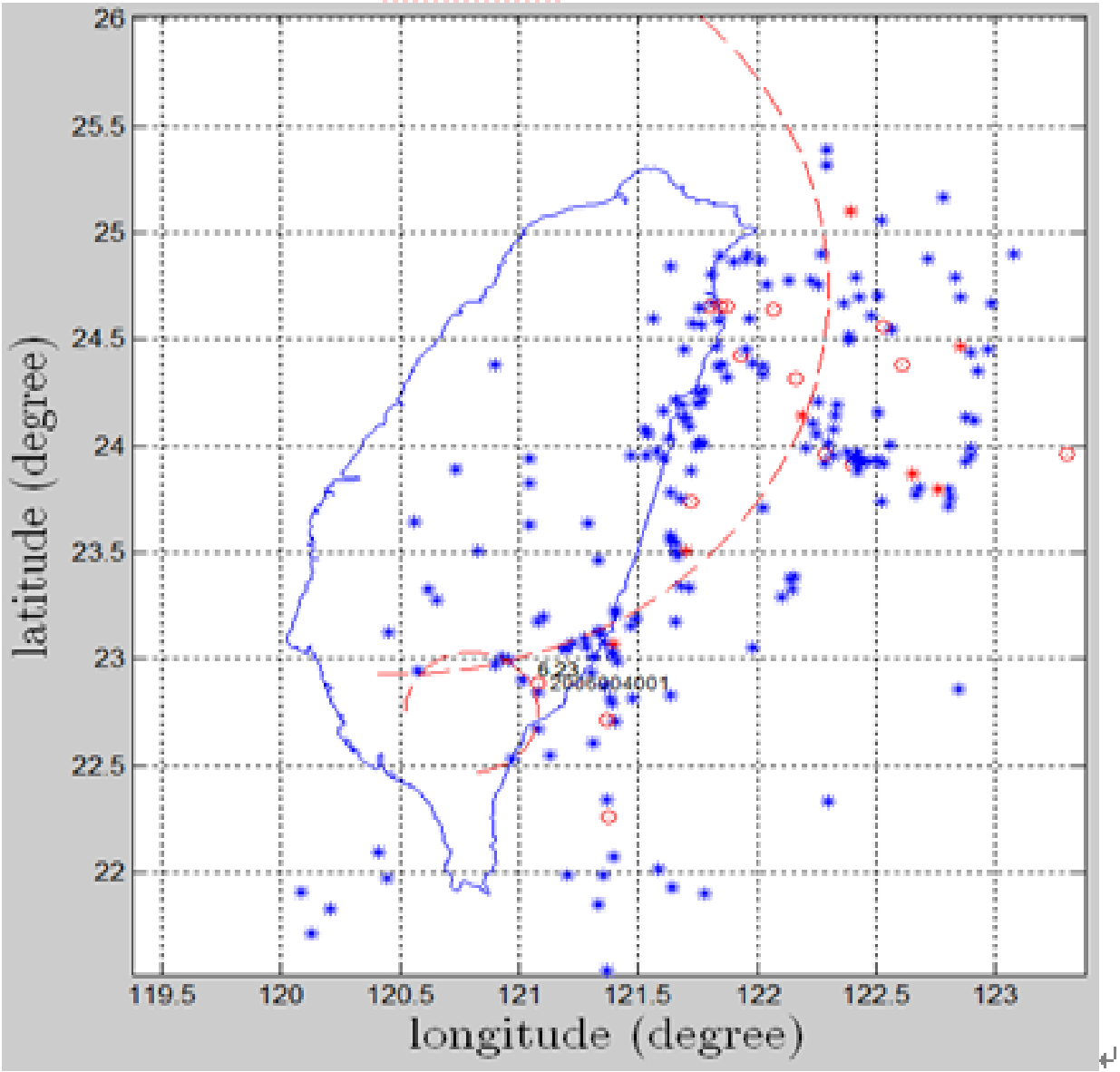


Fig. 20 An event with M=6.23 near the intersection point of two SCAE. It occurred on 2006/4/1 in Taitung.

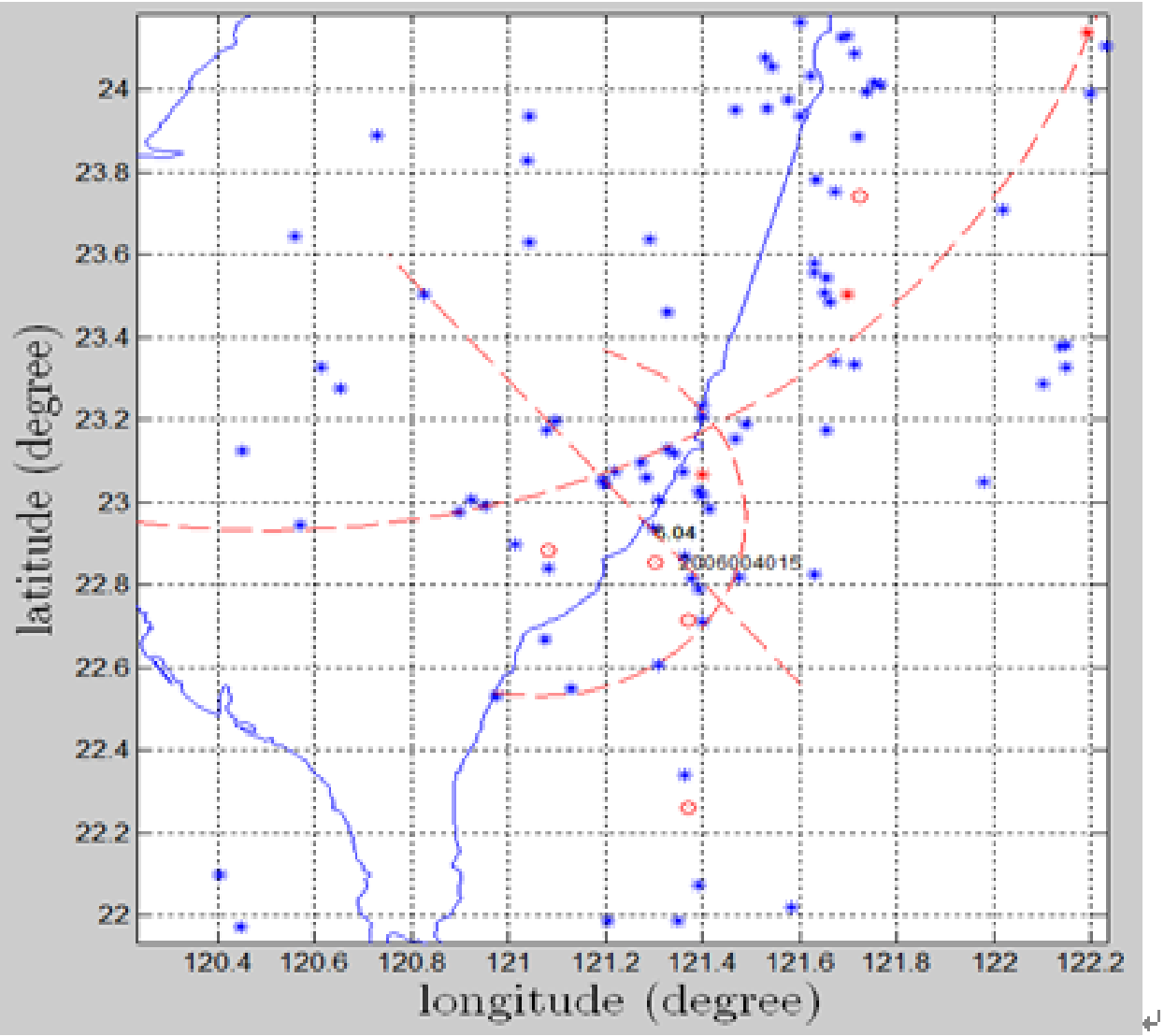


Fig. 21 An event with M=6.04 near the intersection points of a SLE with two SCAE. It occurred on 2006/4/15 under the sea outside Taitung.

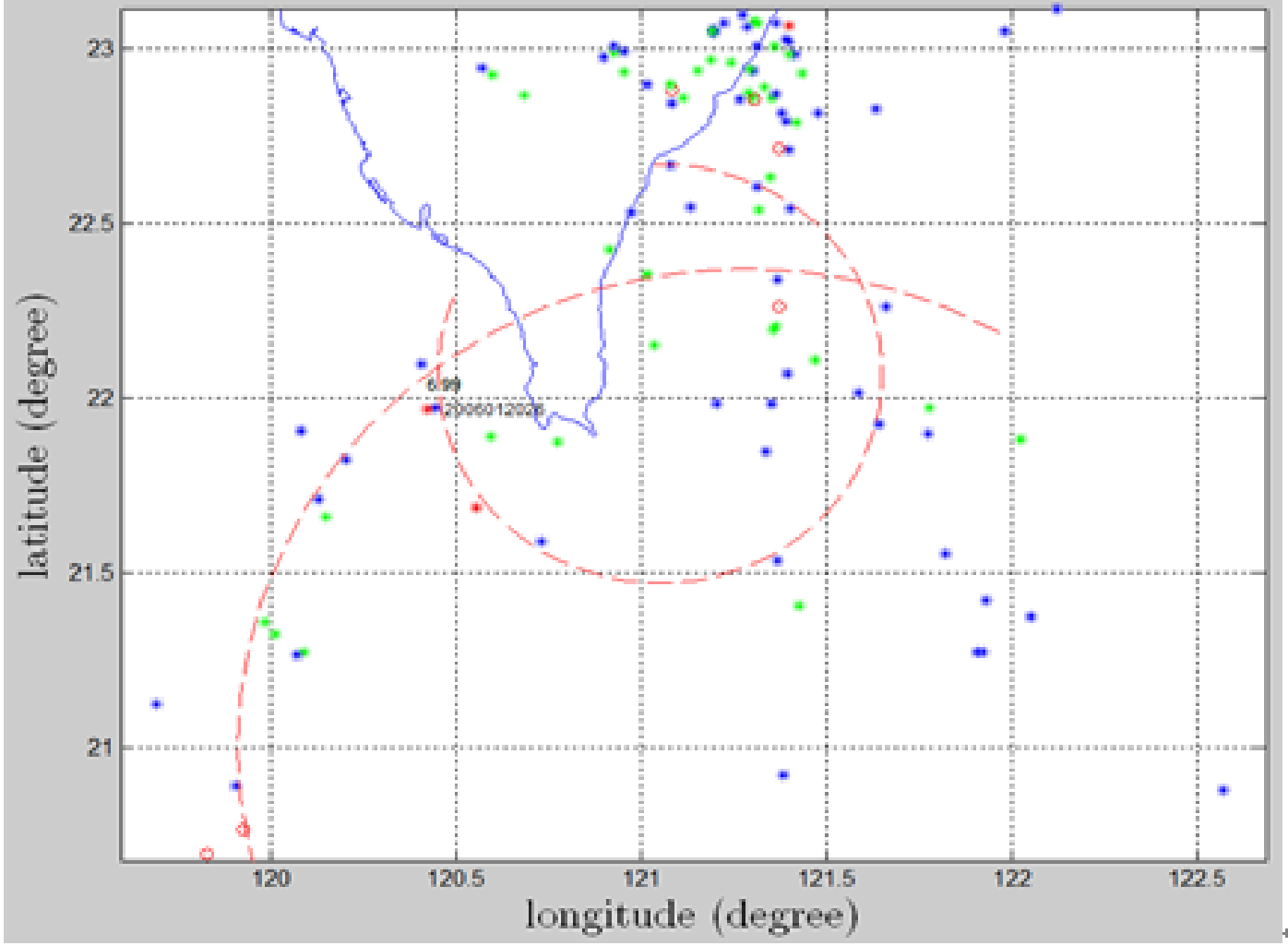


Fig. 22 An event with M=6.99 near the intersection point of two SCAE. It is also near the western end of one of the two SCAE and occurred on 2006/12/26 under the sea outside Pingtung.

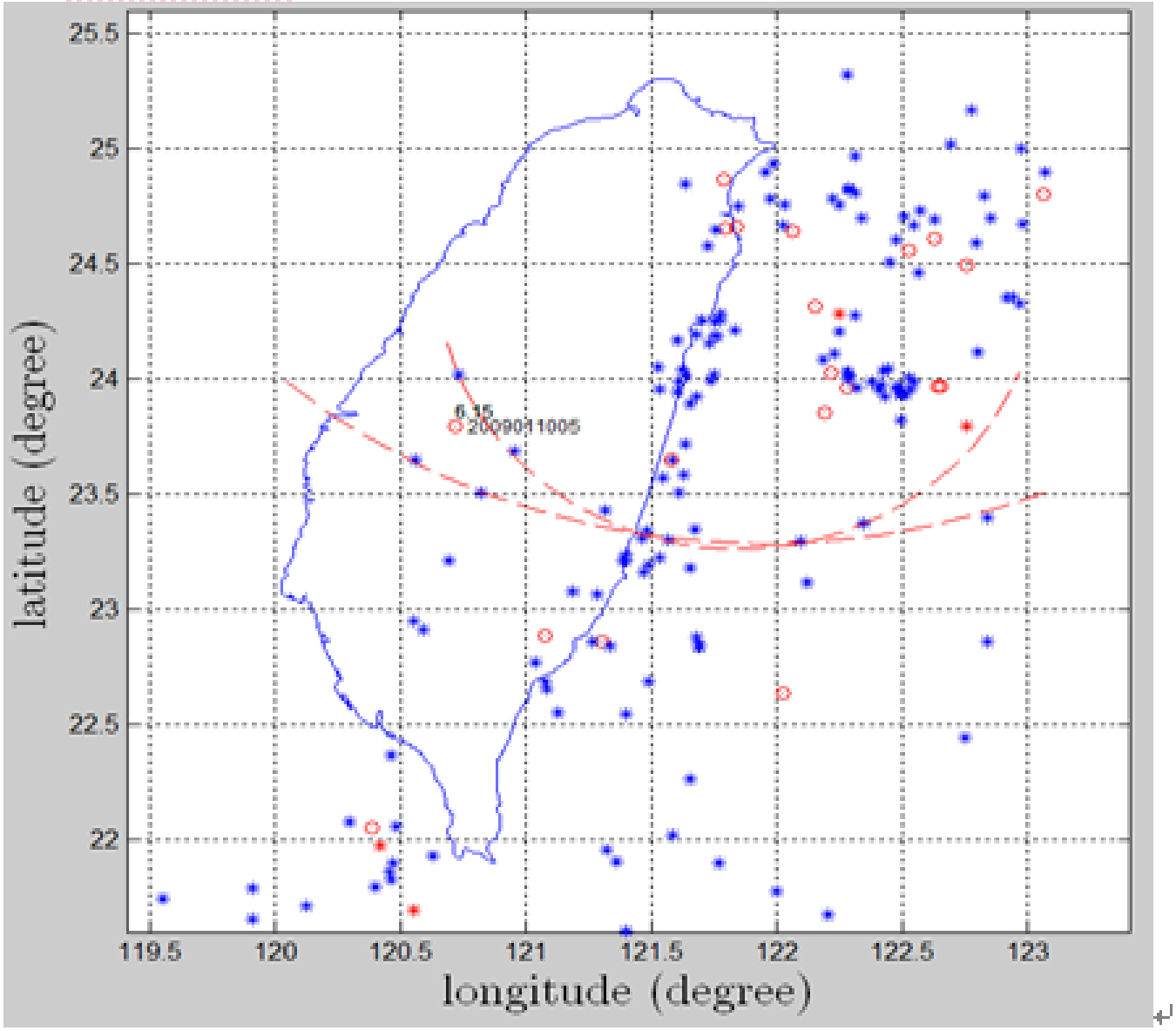


Fig. 23 An event with M=6.15 in a zone between two intersecting SCAE. It occurred on 2009/11/5 in Nantou.

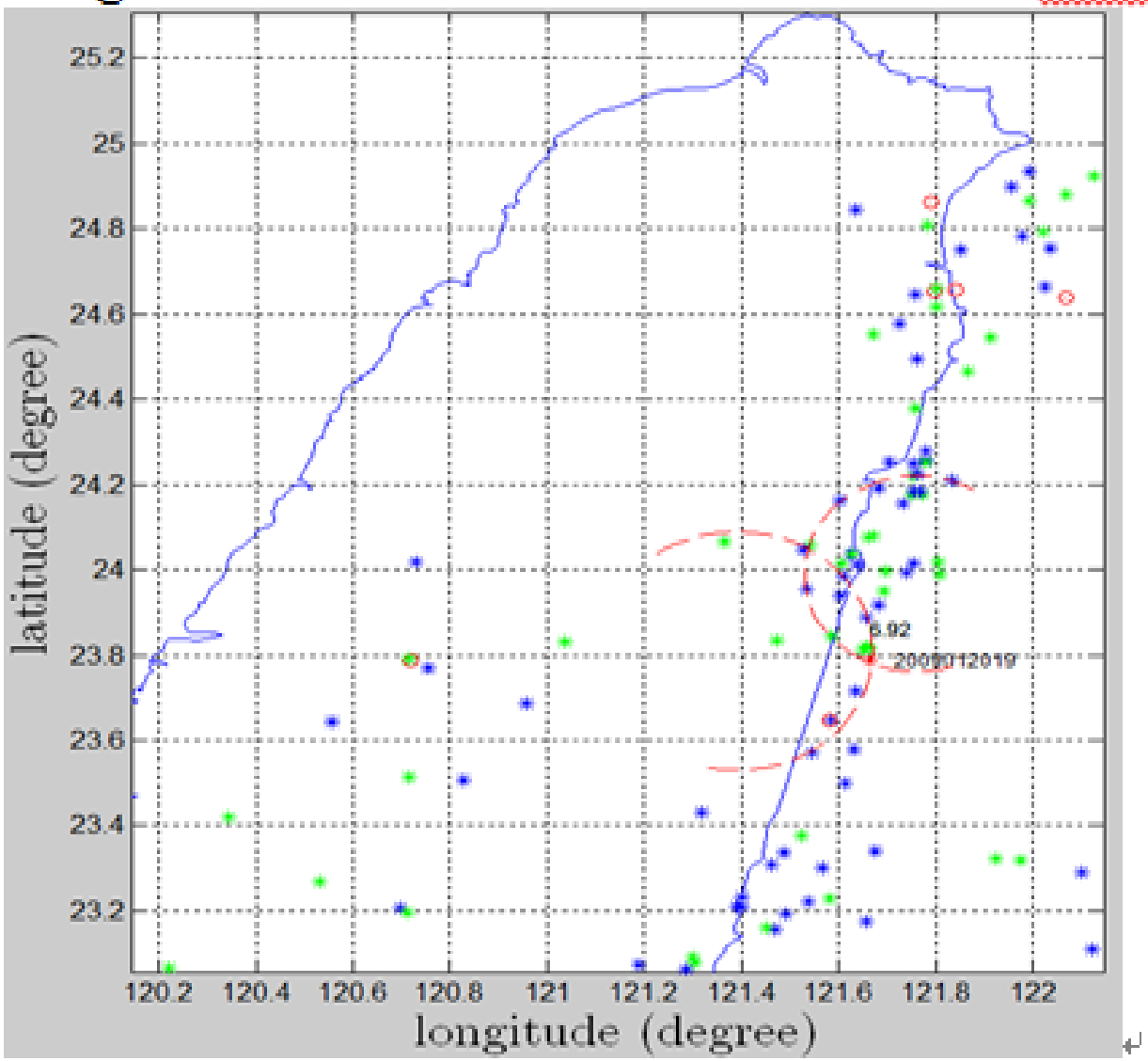


Fig. 24 An event with M=6.92 at an intersection point of a SCAE and an extension arc of another SCAE. It occurred on 2009/12/19 under the sea outside Hualien.

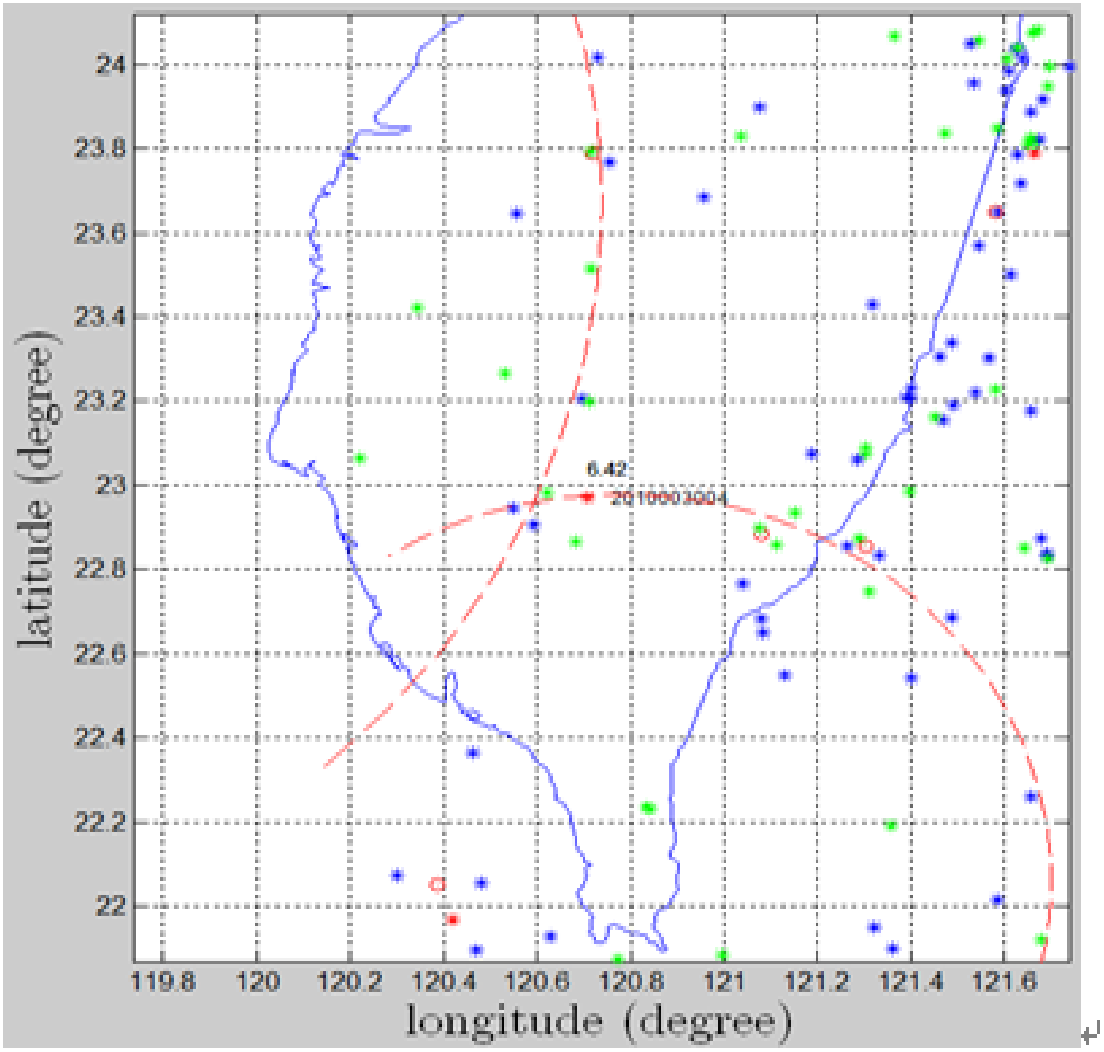


Fig. 25 An event with M=6.42 near the intersection point of two SCAE. It is also embedded near the northern end of one of the two SCAE and occurred on 2010/3/4 in Kaohsiung.

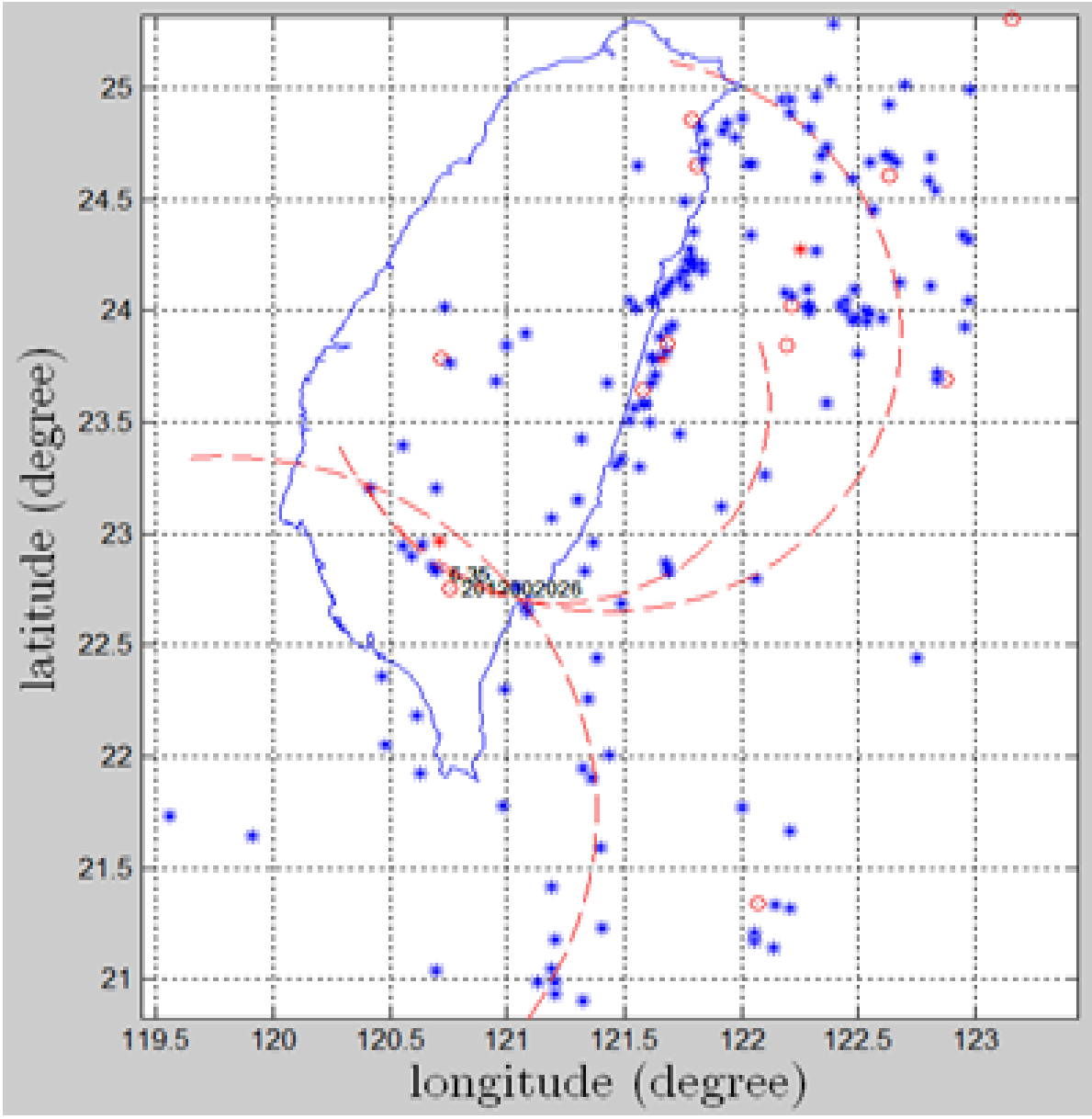


Fig. 26 An event with M=6.35 near the intersection point of three SCAE. It occurred on 2012/2/26 in Pingtung.

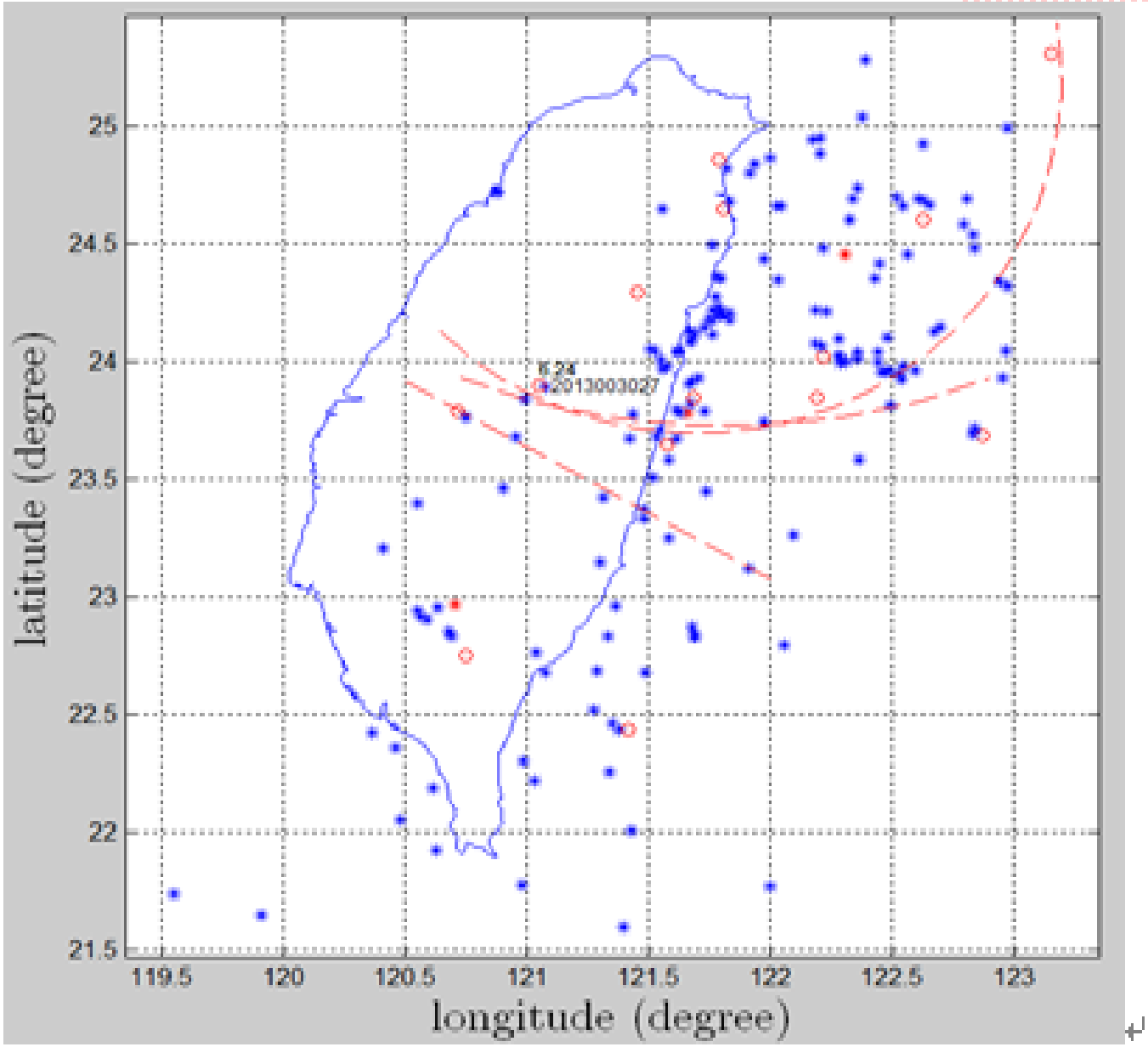


Fig. 27 An event with M=6.24 near the intersection point of two SCAE. It occurred on 2013/3/27 in Nantou.

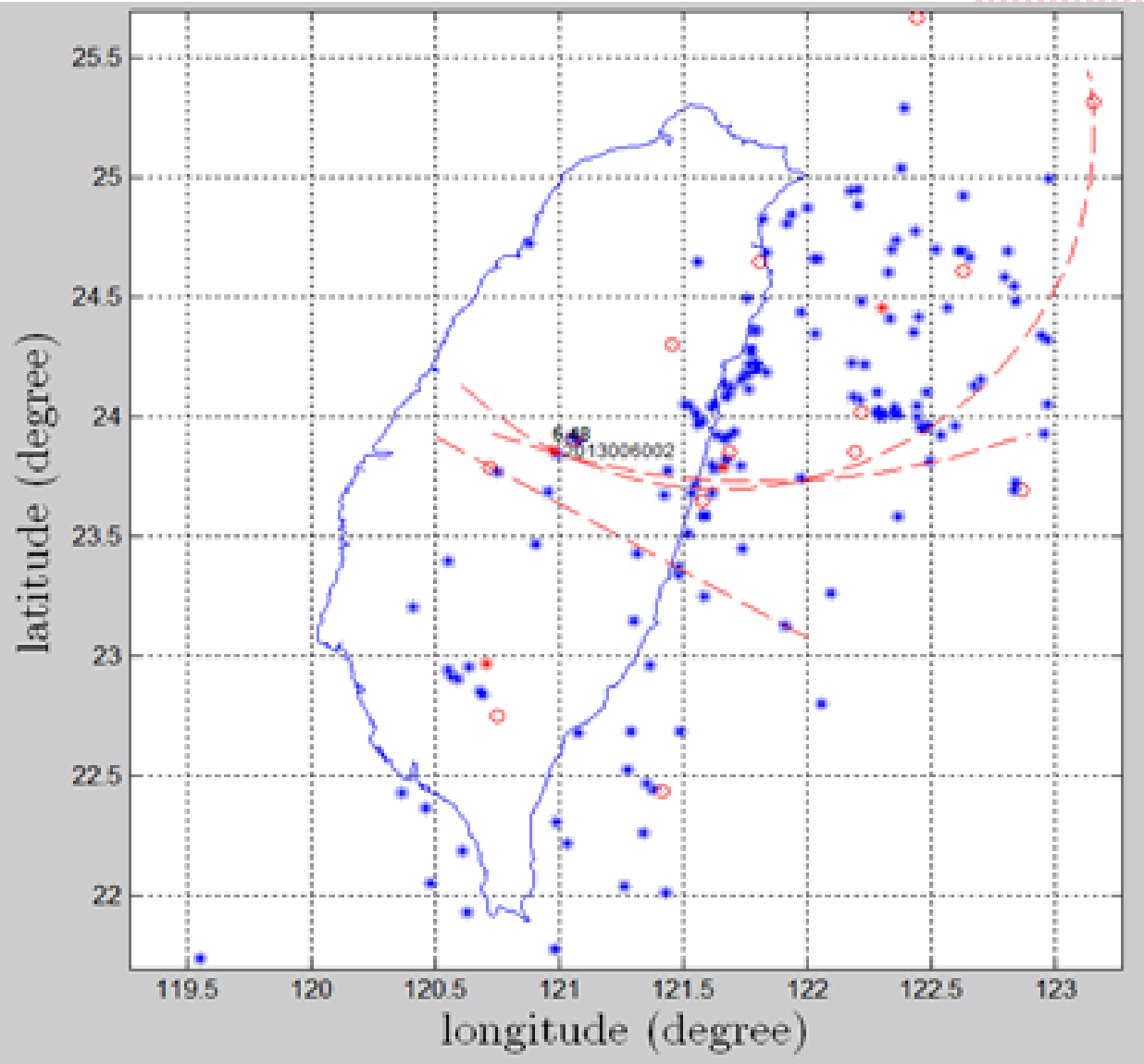


Fig. 28 An event with M=6.48 at one of the two intersection points of two SCAE. It occurred on 2013/6/2 in Nantou.

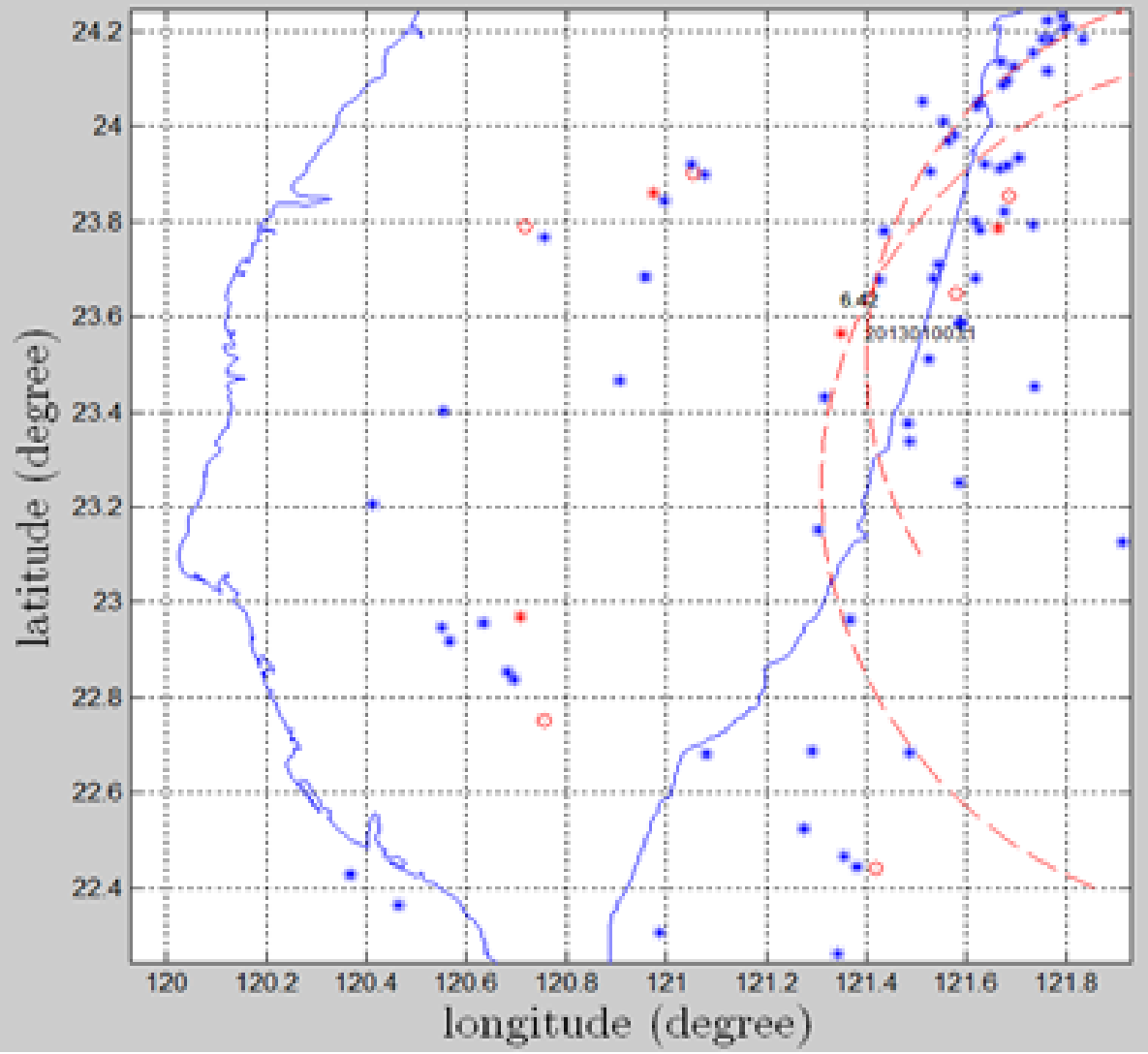


Fig. 29 An event with M=6.42 near the intersection point of two SCAE. It is also near the southern end of one of the two SCAE and occurred on 2013/10/31 in Hualien.

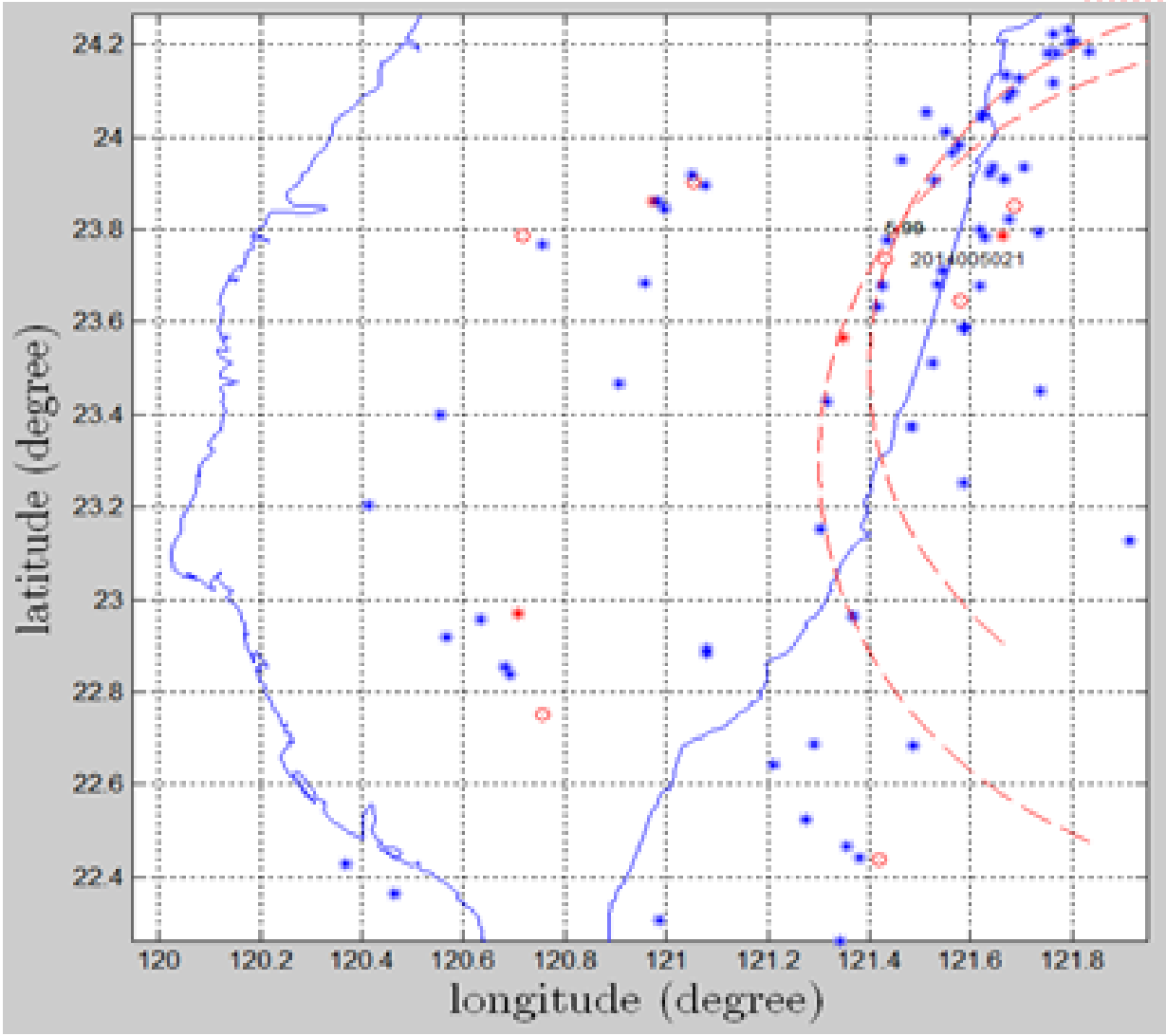


Fig. 30 An event with M=5.99 near the intersection point of two SCAE. It is also near the southern end of one of the two SCAE and occurred on 2014/5/21 in Hualien.

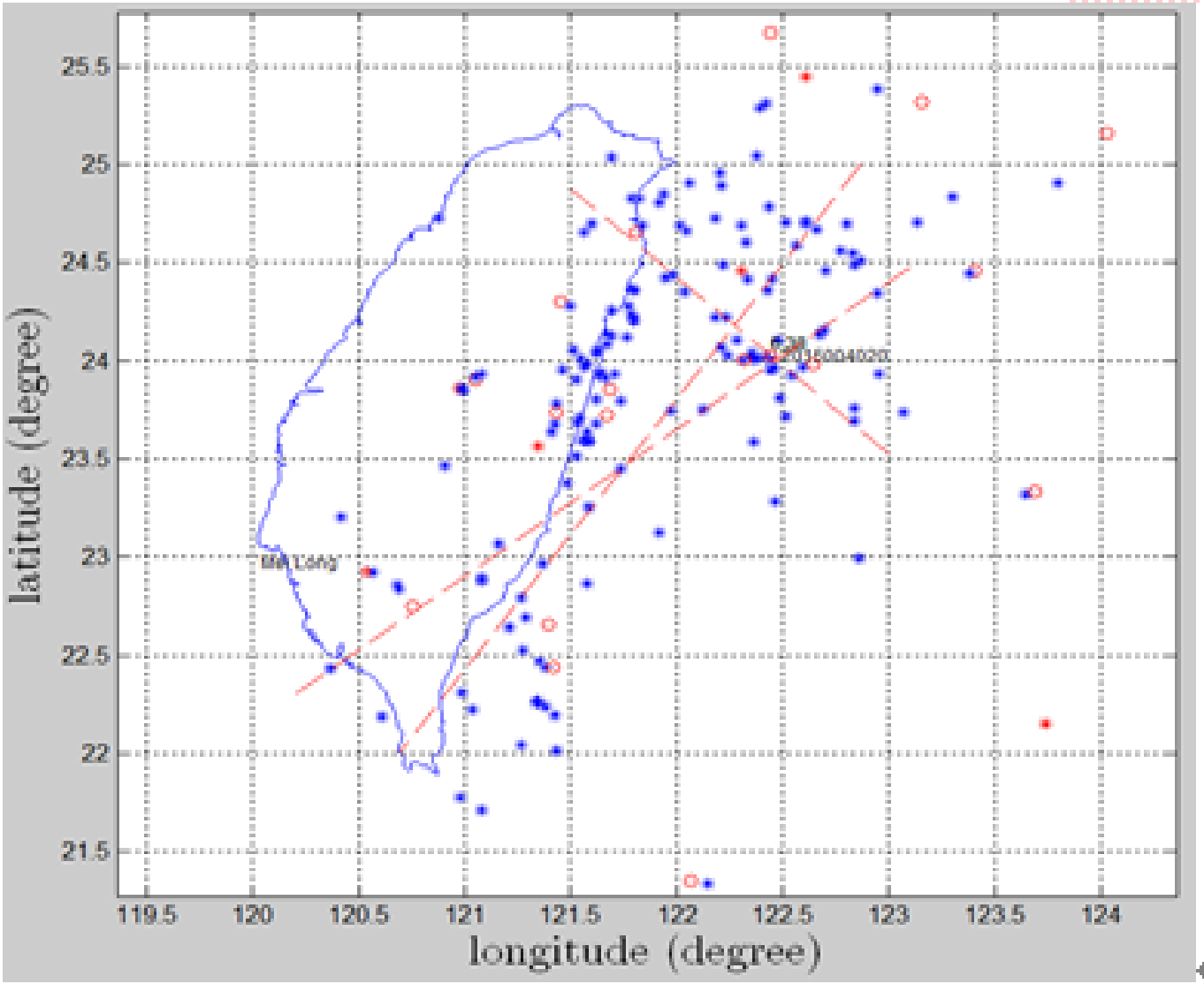


Fig. 31 An event with M=6.38 near the intersection points of a SLE with other two SLE. It occurred on 2015/4/20 under the sea about 80km outside Hualien.

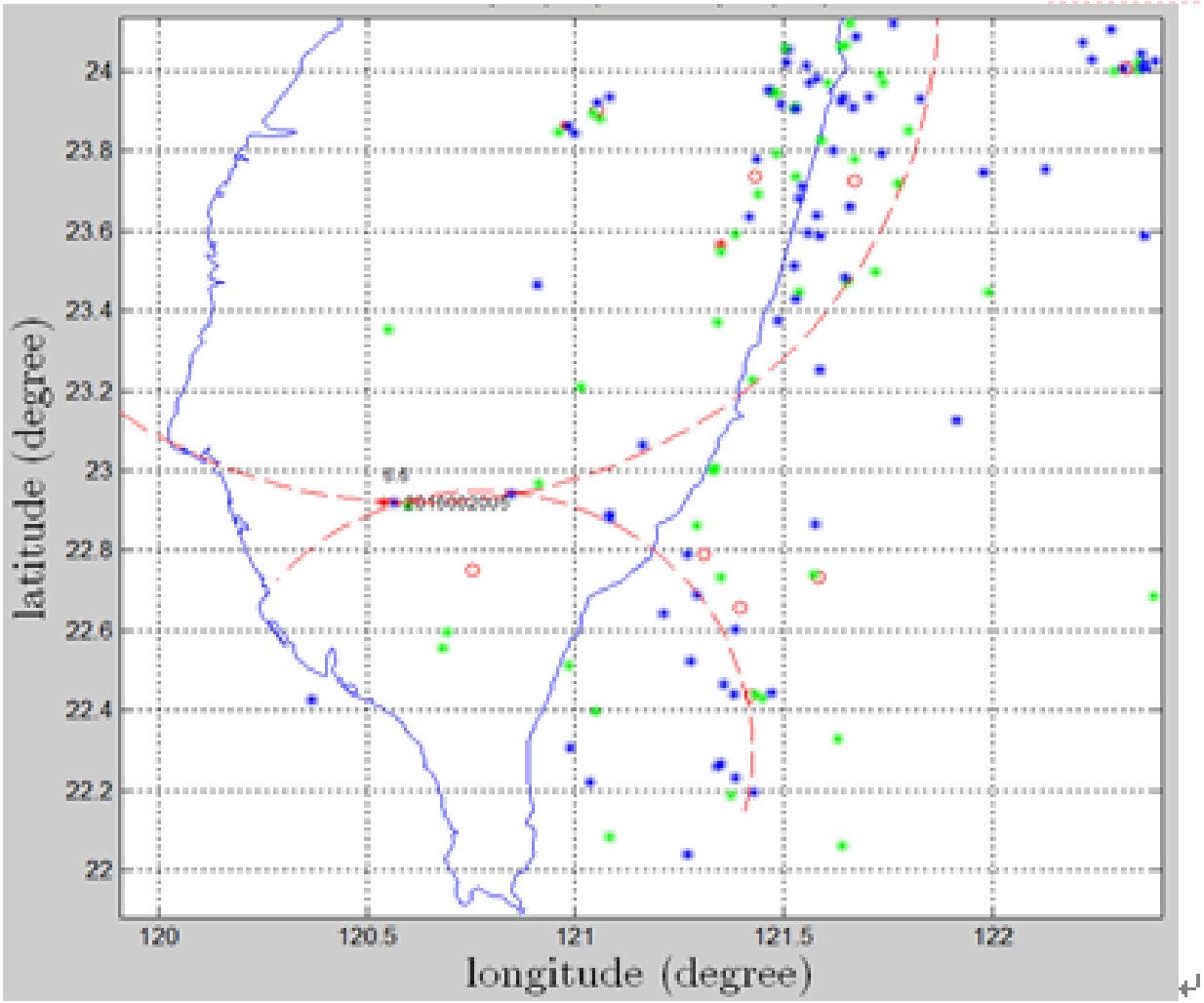


Fig. 32 An event with M=6.6 at one of the two intersection points of two SCAE. It is at the western ends of these two SCAE and occurred on 2016/2/6 in Kaohsiung.

All of the 59 Figures about the intersections of SCAE, SLE,SSCAE and SSLE will be presented also in the master thesis by my student Chieh-Heng Lin finishing this summer. Lin will analysis the detailed properties of all of the intersections in his thesis.

Main results

First, 59 strong earthquakes with M≥5.99 around Taiwan in the last 43 years have been investigated.

It is found that every one of these strong earthquakes occurred near to (within 70 km) at least one intersection point of two members of SE within two or three years after the appearance of the intersection point.

These might be caused by the interactions of two (or more) stress localization processes in different directions.

Main Results

Second, a three-step method is proposed for the prediction of the *approximate* locations and occurrence times of future strong earthquakes by monitoring the current as well as the latest events to look for the formations of intersection points of members of SE.

The distance scale of our prediction is smaller than 70km while the time scale is smaller than about 3 years according to the experience of using our method so far.

5) Future Works

1) Double Convex Intersections

Many (all ?) of the 59 strong events occurred around some double convex intersections of strong circular arcs of earthquakes. The details will be clarified in the future by Chieh-Heng Lin, Pei-Yun Sun and me.

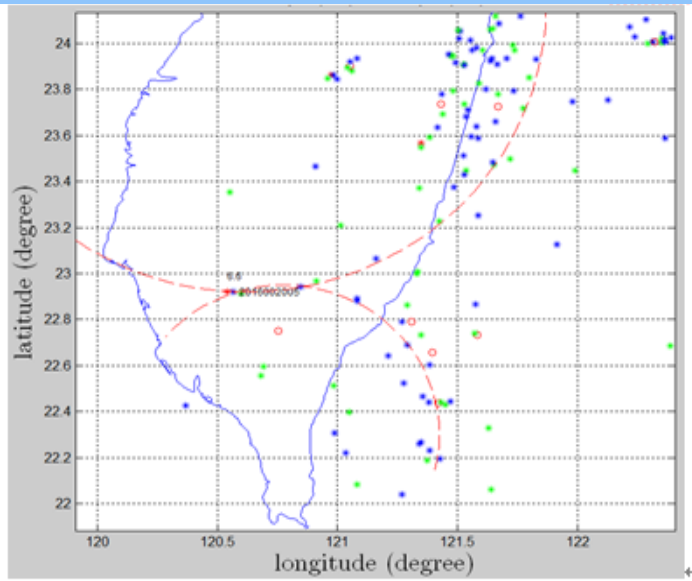


Fig. 32 An event with M=6.6 at one of the two intersection points of two SCAE. It is at the western ends of these two SCAE and occurred on 2016/2/6 in Kaohsiung.

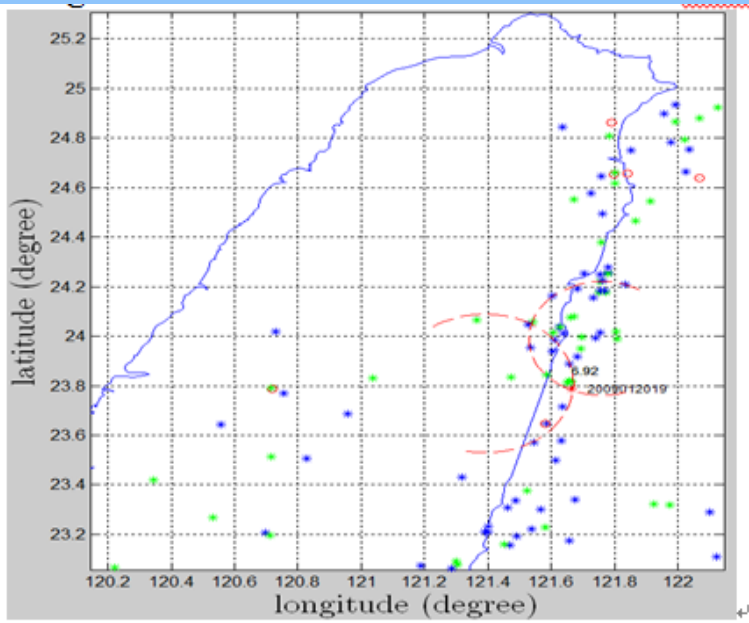


Fig. 24 An event with M=6.92 at an intersection point of a SCAE and an extension arc of another SCAE. It occurred on 2009/12/19 under the sea outside Hualien.

2) Predicting Strong Earthquakes from Intersections of SCAE (and/or SLE, SSCAE, SSLE)

validity of $p \rightarrow q$ doesn't mean that $q \rightarrow p$ holds

If a strong event occurs at (x,y) (p) then there is an intersection point (by the previous data in 5 years) near to (x,y) (q).

(Inference from the 59 strong earthquakes studied by us)

The following inverse relation may not be true:

If there is an intersection point at (x*,y*) (by the previous data in 5 years) (q*) then a strong event will occur near to (x*,y*) within 3 years (p*).

The following inverse relation may not be true:

If there is an intersection point at (x*,y*) (by the previous data in 5 years) (q*) then a strong event will occur near to (x*,y*) within 3 years (p*).

The following statistical statement of the inverse relation may work:

If there is an intersection point (by the previous data in Ni years) (q*) then there is a Np% of chance that a strong event will occur nearby within Nf years (p*).

(Ni might be 5 or less than 5, Nf might be 2 or 3, they should be determined from statistics. In different regions of the world, their values may be different.)

If there is an intersection point (plotted by the previous data in 5 (or 4) years) (q*) then there is a Np % of chance that a strong event will occur nearby within Ny years (p*).

(The three-step method proposed in the previous conference paper.)

The values of Np and Ny are obtained from the statistical analysis of the SCAE, SSCAE, SLE, and SSLE around Taiwan in the past 40 years.

(Carried out by Ming-Huang Chen, Yen-Yu Chen, Yu-Chien Shih, Wei-Yuan Tsai, Jin-Ping Yu and me.)

3) Prediction of Not Occurrence of Strong Earthquakes

validity of $p \rightarrow q$ holds mean that $\sim q \rightarrow \sim p$ holds

If a strong event occurs (p) then there is an intersection point (plotted by the previous data in 5 years) nearby (q). (Inference from the 59 strong earthquakes studied by us)

The negative expression of the above statement:

If there is no intersection point (plotted by the previous data in 5 years) at a place (~q*) then no strong event will occur nearby within T years (~p*).

The value of T can be determined from statistics of the past earthquake catalog.

Is 59 strong events enough to guarantee the validity of the T value we will get in the future? We may have more strong events to add in in the future. The strong events in other places like Japan and US can also be analyzed to increase the number of the samples.

4) Strong Events and SCAE (SLE) in Other Places

Are our results valid in other places (with different mechanical enviroments)

1)Taiwan area : plate squeeze, compressive stresses rather than extensional stresses.

2)US: the San Andreas Fault at California (right-lateral strike-slip (horizontal) motion)

3)Other areas

(analyzed by Chiu-Tsen Hung and me)

5) Magnitude, Time, and Length Correspondences

MSE=Magnitude of the strong earthquake

MMSS=Minimum magnitude of the events near to the spatial points along the SCAE, SLE, SSCAE, or SSLE related to the intersection point

MSE	MMSS
M6.8 (121.8E 24N, 1986/11/14)	M5.13
M6.5 (121.6E 23.9N, 1990/12/13)	M5.10
M6.5 (121.8E 24.5N, 1994/6/5)	M5.11
M6.5 (121.6E 24.5N, 1995/6/25)	M5.11
M6.2 (120.7E 23.5N, 1998/7/17)	M4.86
M7.3 (122.7E 23.5N, 1999/9/20)	M5.26
M6.7 (121.1E 23.9N, 2000/6/10) M6.1(120.9E 23.4N, 2000/7/28)	M5.15 M5.07

Is a Strong SCAE

1) Longer (?)
2) More spatial points(?)
3) Formed in a shorter time period(?)
4) The minimum magnitude of the events near the spatial points is higher(?)

Conjecture :

Near to a stronger main shock an intersection by two SCAE (or SLE) with longer lengths, more uniform spatial points and events with larger magnitudes along it may exist.

This needs to be verified by the earthquake catalogs.

(Recent works of Pei-Yun Sun and Che-Hung Lin --- Master Theses guided by me.)

6) Computor program to search for SCAE

The SCAE obtained so far are by inspection, which are too subjective. We are developing computer program to do this job.

7) Comparison between Chen's Conjugate Bands of Earthquakes and our Intersections of SCAE,SSCAE,SLE, and SSLE

Chen's Conjugate Bands	Our Intersections of SCAE,SSCAE, etc.
1)The bands are generally formed 1-3 years before the main shocks.	1) The intersections are generally formed within 4 or 5 years before the main shocks.
2)The bands are usually several hundred meters long	2) The lengths are usually between 50km and 400km
3)Main shock is located at the intersection point.	3) Main shock is located near to the intersection point within 70 km
4) Minimum magnitude of the events along the bands is M3	4) Minimum magnitude of the events along the SCAE, SSCAE, SLE and SSLE is M4.6
5) The magnitudes of the related main shocks are usually larger than M7.	5) The magnitudes of the related main shocks are usually larger than M5.99.
6) Only conjugate bands found before 8 major earthquakes (M≥7) in the literatures. No conjugate bands had been found before earthquakes with M≥5 and M≥6.	6) Intersections of SCAE, SSCAE, SLE, SSLE have been found before all the 59 strong earthquakes (M≥5.99)

We will try to apply both of our theory and that of Chen to analyze the strong and major earthquakes around Taiwan and other places of the world in the future.

Acknowledgement

About 10 years ago, Prof. Chien-Chih Chen taught me how to analyze earthquake catalog by using concepts such as pattern informatics (PI) and relative intensity (RI). He also sent me one free copy of the book by C.H. Scholz and taught me many important concept about earthquake events. All of these are deeply appreciated.

Over 15 students help me in analyzing earthquake catalogs. Their helpful comments are highly appreciated.

I am also grateful to my sons Edward and Gordon for their encouragement and endless confidence in my research of earthquake prediction. They never doubt at me even at the time when my confidence was shaking.