Tectonic Stress Distribution of New Zealand

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New Zealand is considered as one of the most active earthquake sources in the world, experiencing the deadly 2011 M6.3 at Christchurch, as well as more than 180,000 earthquakes from 1964 to 2016. One important parameter in earthquake statistics is the b value in the frequency magnitude distribution (Gutenberg and Richter, 1954). There have been a number of observations that indicate that changing in b value is inversely related to changes in the stress level. An earthquake is caused by sudden release of seismic waves. Hence, this study was conducted to evaluate the spatial distribution of b value at New Zealand, implicating for prospective areas of the upcoming earthquakes.

In this study, we considered the large earthquake, $M_w \geq 7.0$, because they can result more vulnerable to the country. By the retrospective test, the appropriate parameter to calculate b value was 50 fixed earthquake events. After we got the suitable condition for b-value calculation, we analyzed the most recent earthquake data (1964 – 2012) and mapped the spatial distribution of b value of New Zealand. The result revealed that there are 11 anomalous of low b-value areas. The study showed there are five areas that were hit by the large earthquake before. After that, the b value had been increasing because of stress releasing. However, the b values of these areas have been decreasing, which means the stress have been increasing and these anomalous areas may potentially generate large earthquake up to 7.0 M_W.

Department : GEOLOGY Student’s Signature ....

Field of Study : GEOLOGY Advisor’s Signature ....

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พงษ์ลดา นิยมพงษ์ : การกระจายตัวของความเค้นทางธรณีแปรสัณฐานของประเทศนิวซีแลนด์. (Tectonic Stress Distribution of New Zealand) อ.ที่ปรึกษาวิทยานิพนธ์: รศ.ดร. สันติ ภัยหลบลี้, 46 หน้า

ประเทศนิวซีแลนด์ตั้งอยู่บนแผ่นเปลือกโลกแปซิฟิกมุดตัวอยู่ใต้แผ่นเปลือกโลกออสเตรเลีย และมีรอยเลื่อนขนาดใหญ่ผ่านกลางประเทศคือ รอยเลื่อนอัลไพน์ (Alpine fault) จนทำให้เกิดแผ่นดินไหวบ่อยครั้งในแต่ละปี หลายครั้งเป็นเพียงแผ่นดินไหวขนาดเล็กที่ไม่ส่งผลต่อชีวิตประจำวัน แต่บางครั้งก็เกิดแผ่นดินไหวขนาดใหญ่ที่สร้างความเสียหายมหาศาลต่อทรัพย์สินและชีวิตของผู้คน ดังเช่น แผ่นดินไหวไครสต์เชิร์ช ค.ศ. 2011 ที่ก่อให้เกิดบ้านเมืองพังพินาศรวมถึงมีผู้เสียชีวิต และล่าสุดคือแผ่นดินไหวไคคูร่า ค.ศ. 2016 ที่มีขนาดถึง 7.8 แมกนิจูด ดังนั้นการศึกษาพฤติกรรมแผ่นดินไหวในอดีต จะทำให้สามารถทำนาย (forecast) พฤติกรรมแผ่นดินไหวในอนาคตได้ ก่อให้เกิดการเฝ้าระวัง ป้องกัน และลดความเสียหายที่เกิดจากภัยพิบัติธรรมชาตินี้

แผ่นดินไหวที่มีสาเหตุมาจากธรรมชาติ เกิดจากการปลดปล่อยพลังงานเพื่อลดความเครียดที่สะสมไว้ภายในโลกออกมาเพื่อปรับสมดุลของเปลือกโลกให้คงที่ โดยพื้นที่ใดที่มีความเค้นสะสมตัวอยู่มาก จะมีโอกาสเกิดแผ่นดินไหวมากตาม จึงเป็นที่มาของงานวิจัยนี้ โดยศึกษาค่าคงที่ b ในสมการกูเตนเบิร์กและริกเตอร์ (1954) ซึ่งค่าคงที่ b มีความสัมพันธ์เชิงแปรผกผันกับความเค้น หมายความว่าพื้นที่ใดมีค่า b ต่ำพื้นที่นั้นมีความเค้นสูง ซึ่งมีโอกาสเกิดแผ่นดินไหวได้ในอนาคตหากมีการปล่อยพลังงานจากความเค้น

การศึกษาหาค่า b จากข้อมูลแผ่นดินไหวในอดีตที่แผ่นการคัดกรองแล้ว แต่ละพื้นที่จะมีตัวแปรในการวิเคราะห์ที่เหมาะสมแตกต่างกัน จากการศึกษาย้อนกลับพบว่า หากกวาดรัศมีใดๆออกไปจากพื้นที่ตามจำนวนแผ่นดินไหว 50 เหตุการณ์ จะทำให้ได้ค่าที่เหมาะสมที่สุดในการวิเคราะห์ค่า b ของประเทศนิวซีแลนด์ เมื่อนำค่านี้มาศึกษาต่อจะได้แผนที่การกระจายตัวของค่า b ของประเทศนิวซีแลนด์ในปัจจุบัน พบว่าปัจจุบันมี 11 พื้นที่ที่มีค่า b ต่ำลงเรื่อยๆ หมายความว่าพื้นที่เหล่านี้มีกำลังสะสมความเค้นเพิ่มมากขึ้น แสดงว่ามีโอกาสเสี่ยงในการเกิดแผ่นดินไหวในอนาคตได้

ภาควิชา ธรณีวิทยา ลายมือชื่อนิสิต

สาขาวิชา ธรณีวิทยา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์

ปีการศึกษา 2559

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INTRODUCTION

1.1. Theme and Background

New Zealand is known for one of the most seismically active areas of the world. It is located where the Pacific Plate is subducted below the Australian Plate, the two plates grind past each other along the Alpine fault. As two plates push together, the boundary becomes more stressed then eventually an earthquake occurs. That's the reason why New Zealand hit with more than 10,000 quakes every year by both of small and severe earthquake. Experiencing the deadly in 2011 6.3 M_w at Christchurch is highly vulnerable for life and properties.

There have been a number of observations that indicate that there is a relation may hold for earthquake, which is the Gutenberg-Richter law. There is a number called b value in the frequency-magnitude distribution. The seismologists found that b value decreases linearly with increasing differential stress. The higher stress in the continental lithosphere can lead to earthquake. Consequently, this research evaluated the prospective area by studying the b values.

1.2. Study Area

The study area is located on New Zealand, 167E to 178E latitude and 34S to 47S longitude. It is the border between the Australian and Pacific plates which grind past each other along the Alpine fault as illustrated in Figure 1.1.

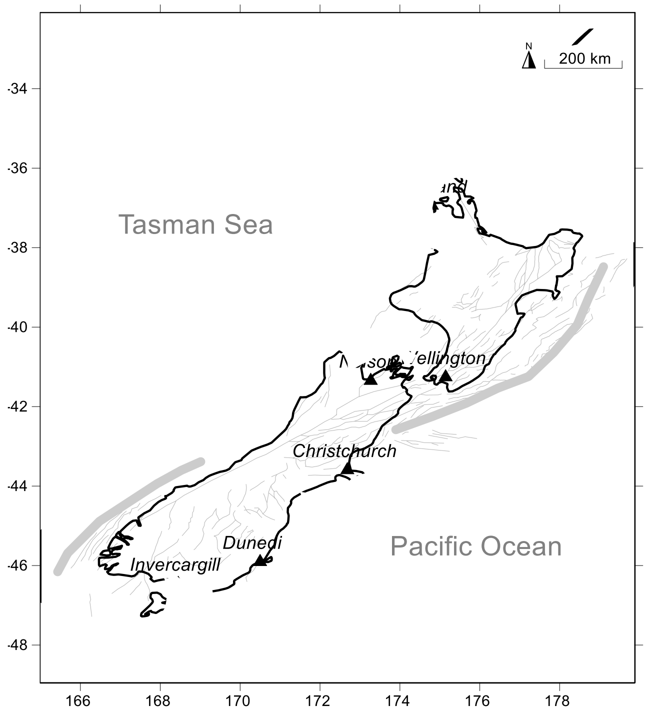


Figure 1.1. Map showing the study area of New Zealand, 167E to 178E latitude and 34S to 47S longitude.

1.3. Objective

To evaluate the risk area for upcoming earthquake of New Zealand by studying variation of seismic b values.

1.4. Scope of Study

To analyze the seismic b values of New Zealand covers 167E to 178E latitude and 34S to 47S longitude, by using data from instrumental earthquake record and the international earthquake database.

1.5. Expected Output

Mapping of b-value anomalies of New Zealand: Implications for upcoming earthquakes.

CHAPTER II

THEORY AND LITERATURE REVIEW

2.1. Relevant Theory

In the early years of seismology, Gutenberg and Richter (1954) presented that the size distribution of earthquakes can be described by a power law relationship. That is the Gutenberg-Richter relation or the frequency – magnitude distribution (FMD), is well known empirical formula in earthquake seismology which shows the frequency of occurrence of earthquakes as a function of magnitude as shown in Equation (2.1).

$$\mathrm{Log}_{10}\, N = a - bM \qquad \text{Equation (2.1)}$$

That *N* is the cumulative number of earthquake with magnitude equal or greater than *M*, where *a* and *b* are constants number. The parameter a describes the total number of earthquakes. While the parameter b, often referred to b values, describes their relative size distribution.

The b value has been observed to change spatially and temporally. There are several studies revealed that Changing in b value is inversely related to changes in the stress level (Allen et al., 1965; Mogi, 1967; Scholz, 1968). A smaller b value probably means that the stress is high (Bufe, 1970; Gibowicz, 1973). Therefore, high and low shear stresses may cause earthquakes with low and high b values (Wyss, 1973; Schorlemmer et al., 2005).

There have been a number of studies that found that the b value for earthquakes in the continental crust decreases approximately linear with depth (Mori and Abercrombie, 1997; Spada et al, 2013). Furthermore, the b value depends on systematically on earthquake mechanism. For example, it has an intermediate value for strike-slip earthquakes, while thrust faulting has smaller number than normal faulting events (Gulia and Wiemer, 2010; Schorlemmer et al., 2005).

2.2. Literature Review

2.2.1. Nuannin et al. (2005)

Nuannin et al. (2005) examined the distribution of b values in Andaman-Sumatra region then applied to precursor of earthquake. The study showed the areas that had low b values (blue color in the map) were the epicenter of the main earthquake event (Figure 2.1).

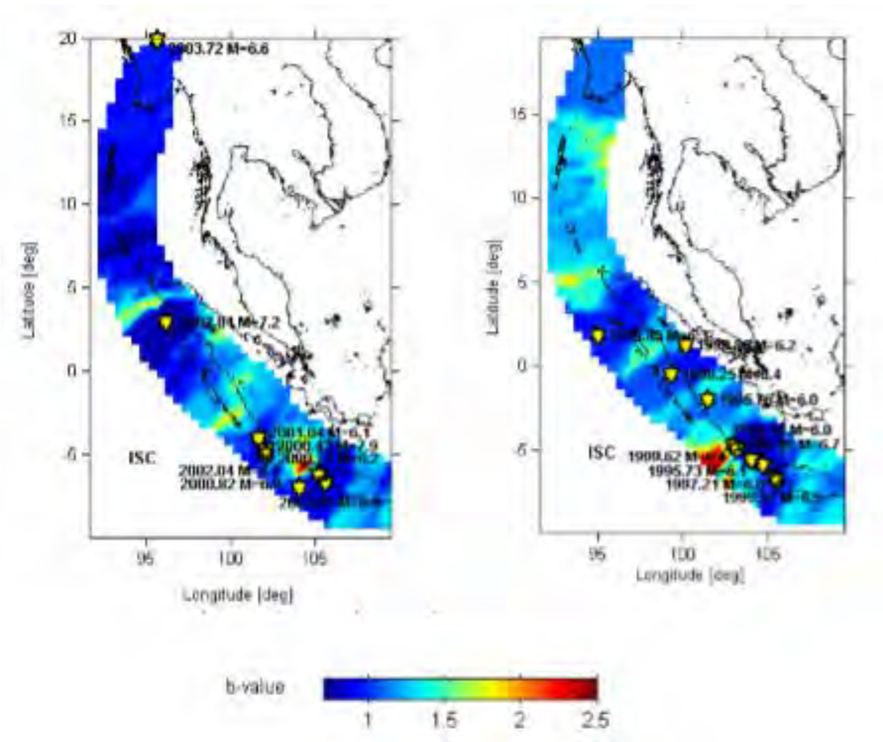


Figure 2.1. Map showing the distribution of b values of Sumatra-Andaman region, 1995-1999 (left) and 2000-2003 (right). The blue presents the low b-values which match with the epicenter (yellow star).

2.2.2. Pailoplee (2013)

Pailoplee (2013) conducted a study to investigate the distribution of the b values along the Sagaing fault zone (SFZ), central Myanmar. The result revealed two prospective areas along the SFZ and at least four areas beneath the SFZ trace that showed low b value anomalies and implied high stress asperities (Figure 2.2).

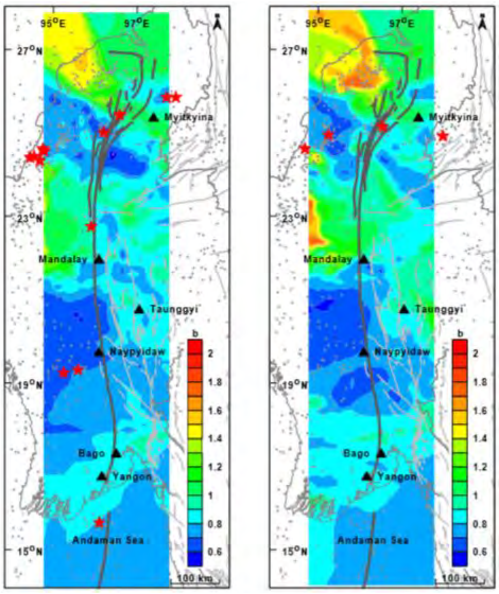


Figure 2.2. Mapping of b value anomalies of the SFZ in 1980–2005 (left) and 1980–2010 (right). The epicenters (red star), m_b ≥6.0, match with the low b value areas (blue).

2.2.3 Pailoplee (2016)

Pailoplee (2016) examined the distribution of b values on Thailand–Myanmar border. By the retrospective test, the study found that the low b values matched with the epicenter of the large earthquake (Figure 2.3). This brought about to reveal five areas of low b-value anomalies along the strike-slip fault system (SSFS) on the Thailand-Myanmar border.

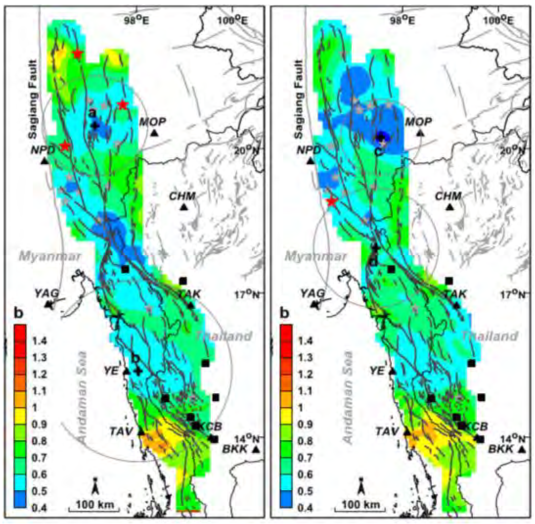


Figure 2.3. Maps showing b value anomalies along SSFS. The epicenters of large earthquake match with the low b values (red star on blue area).

2.3. Methodology

The research methodology used in the study can be classified into 8 methods.

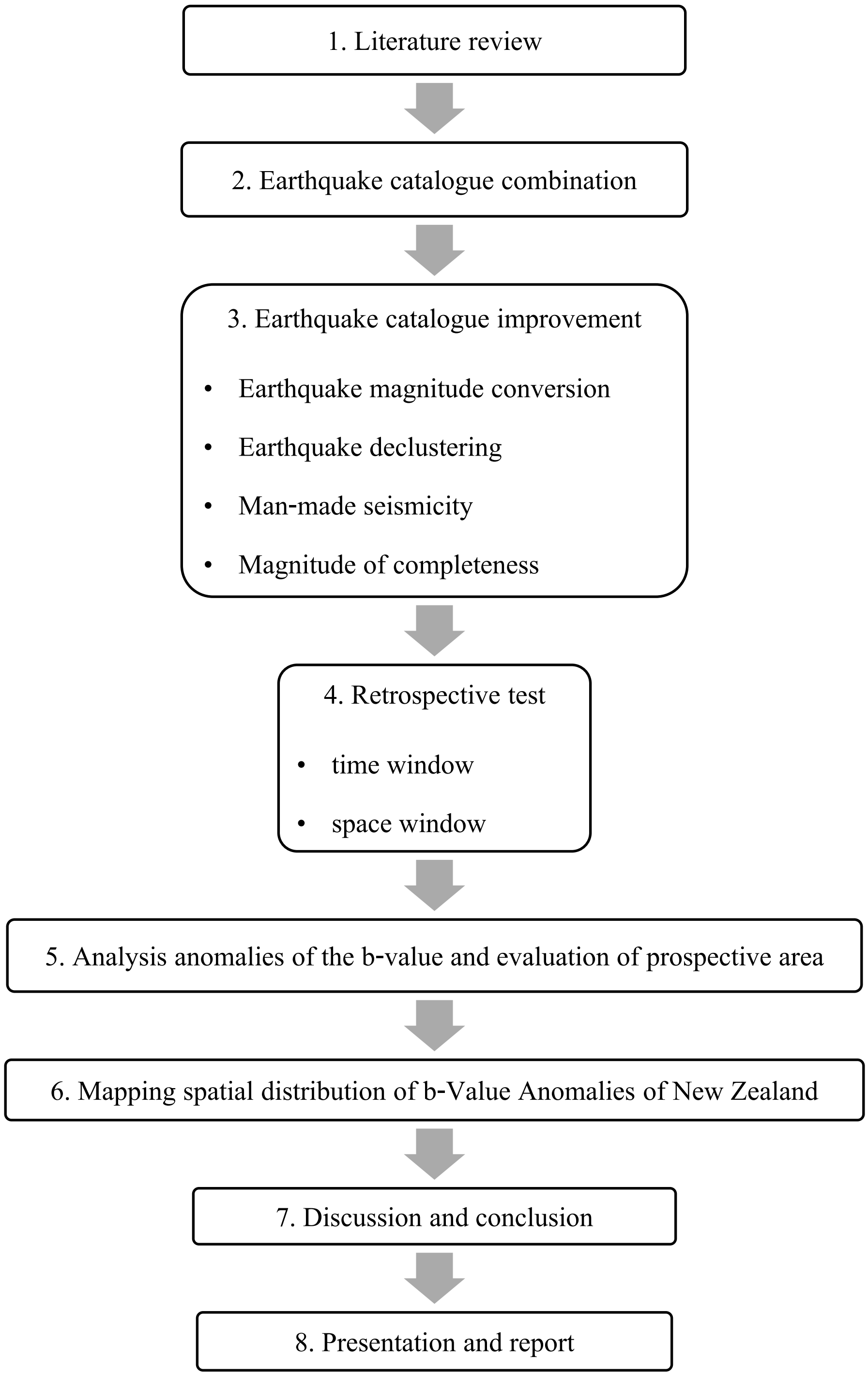


Figure 2.4. Flow chart showing the research methodology recognized in this study.

CHAPTER III

EARTHQUAKE CATALOGUE IMPROVEMENT

3.1. Earthquake Catalogue Combination

There are several seismic networks register worldwide. Many earthquake catalogues have been published online on the internet. The data for the earthquake catalogue preparation was recorded by the following details and showed the parameters of catalogs used in Table 3.1.

1. Coordinate system in Latitude/Longitude of epicenter
2. Date of the earthquake events in Year, Month, and Day
3. Time of the earthquake events in Hour, Minute and Second
4. Magnitude and magnitude scale, the seismic instrument can record more than one seismic wave in the same event. Therefore, the magnitude must be converted to have same types in the next step.

Table 3.1. List of the earthquake catalogue utilized as the main dataset in this study.

Lon	Lat	Year	Month	Day	M_W	M_S	mb	M_L	Depth	Hour	Min	Sec
174.049	-41.77	2013	8	17	5.2	5	5.1	-	19.6	8	58	39
174.337	-41.704	2013	7	21	6.5	6.7	6.1	-	17	5	9	31
174.386	-41.638	2013	7	20	5.7	5.6	5.8	-	14	19	17	10
-176.286	-30.473	2013	7	19	5.7	5.4	5.5	-	21.8	11	40	42
174.408	-41.549	2013	7	18	5.5	5.1	5.7	-	17.5	21	6	39
-177.535	-30.243	2013	7	10	5.6	5.4	5.5	-	10.3	14	44	1
-176.232	-29.787	2013	4	22	5.3	5.1	5.5	-	12.6	23	40	47

This study selected the data from the earthquake catalogue by the following conditions.

- 167E to 178E latitude and 34S to 47S longitude, cover New Zealand
- Magnitude 0.1-10 with depth 0 - 1,000 km and time 1960-2016

3.1.1. The National Earthquake Information (NEIC)

NEIC is a part of United States Geological Survey (USGS). The main mission is determination size and location of all significant earthquakes worldwide, as rapidly and as accurately as possible. It also provides an extensive seismic database to the public.

3.1.2. The International Seismological Center (ISC)

ISC is the organization in charge of USGS. The main purpose is to record the earth's seismic data from over 130 agencies worldwide with highly accuracy. The data consist of epicenters, phase arrival-time, focal mechanism solutions, etc.

3.1.3. The Global Centroid-Moment-Tensor Catalogue (GCMT)

The main activity of GCMT is development and implementation of improved methods for the quantification of earthquake source characteristics on a global scale. The processes spend long time, thus the data public delay but they are the most accuracy.

3.1.4. Data collection result

The first stage in the study is preparation of the earthquake catalogue. The diversity of the data sources and techniques of earthquake location had for its consequence differences in the level of reliability of all main parameters. Since b value analysis are a statically approach, the accuracy of the results grows with the number of earthquakes recorded. Thus, this study used the data from the seismic network of ISC. Because the catalogue contains more than enough events that we can investigate b-values and at least get statistically significant result.

From the data collecting result, there are 182,966 earthquake events in 1964 – 2016. The magnitude is between 0 – 8.1 M_w with depth 0 -827 km (Figure 3.1). The data are plotted to the relative graph between the cumulative number, magnitude, depth and time (year) in Figure 3.2.

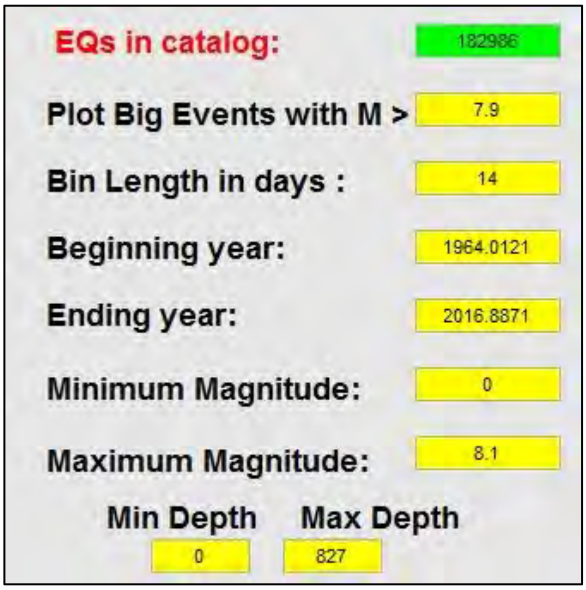


Figure 3.1. The earthquake catalogue from the International Seismological Center (ISC).

a) Magnitude-cumulative number b) Depth-cumulative number c) Time(yr)-cumulative number

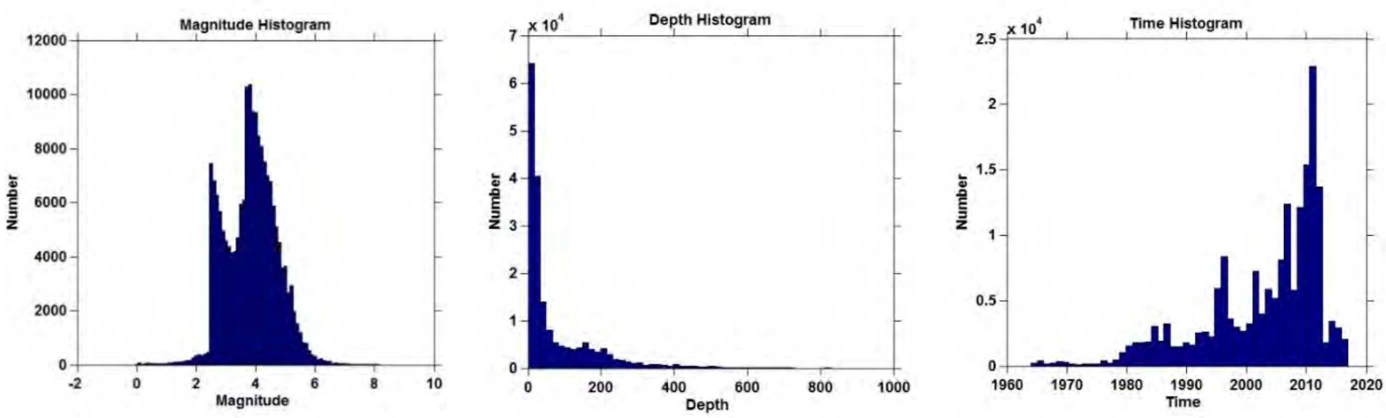


Figure 3.2. The cumulative number of earthquake with a) magnitude b) depth and c) time (year).

3.2. Earthquake Magnitude Conversion

First major problem with earthquake catalogues is the network stores their data in a different form of magnitudes, depending on a seismic wave they use. A variety of different magnitude scales make it difficult to analyze the b value from different catalogues. The database provides these following magnitude types.

a) **M_L** (Local Magnitude) is highly accurate scale for local area. The accuracy is reduced with the epicenter that greater than 650 km. Mostly, M_L is used to estimate the damage of building such as dam, mine and skyscraper.
b) **m_b** (Body-wave Magnitude) is the seismic wave that come in the same time of earthquake. It can be divided into 2 types. There are primary wave (P-wave) and secondary wave (S-wave).
c) **M_s** (Surface-wave Magnitude) is the wave that comes after the body wave reaches earth's surface. In global scale of great distant or large earthquake, the database will record the amplitude's height of surface wave. The data are more complete but can be recorded less than $m_{b.}$
d) **M_W** (Moment Magnitude) is an earthquake measurement from seismic moment, in term of the energy released. Moment magnitude does not depend on an instrument record that make it be the most suitable magnitude types. It is used to estimate magnitudes for all modern large earthquakes.

Furthermore, the database can record the other magnitude types which is M_X. It is the data that not indicate magnitude types. By the way, we define these M_X with $M_{W.}$

Therefore, these earthquake data that come from several sources have different types of magnitude, depend on the instrument record. The past studies found that there is highly error in local magnitude analysis, especially when the recorded network is a great distance from the epicenter. Both body wave and surface wave have their saturation of earthquake magnitude.

The b value estimation depends on the magnitude scales which have a variety of types, such as m_b, M_S, M_W and M_L. In order to analyze this accuracy, it needed to convert these data to have same magnitude. In this study, we gave the consideration to large earthquake because they can cause more vulnerable. The M_W better indicated the size of large magnitude. Hence, the most reliable scale was moment magnitude (M_W).

The method began with finding relationship between two different magnitudes which depended on the area of earthquake event. Then, we selected the most suitable equation by considering R^2, which is known as the coefficient of determination. R^2 is measurement of how close the data are to the fitted regression line. If R^2 closes to 1, it means more accurate.

3.2.1. Moment magnitude (M_w) and body-wave magnitude (m_b)

The Equation 3.1 is relative between moment magnitude (M_w) and body-wave magnitude (m_b) which can be analyzed to the relative graph in Figure 3.3.

$$M_W = 0.0077m_b^2 + 0.4669m_b + 2.5893 \qquad \text{Equation (3.1)}$$

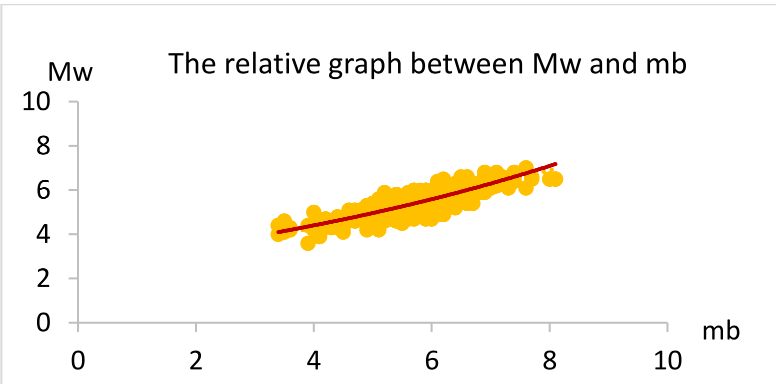


Figure 3.3. The relative graph between M_w and m_b, which the blue are the data in m_b and M_w.

3.2.2. Moment magnitude (M_w) and surface-wave magnitude (M_S)

The Equation 3.2 is relative between moment magnitude (M_w) and surface-wave magnitude (M_S) which can be analyze to the relative graph in Figure 3.4.

$$M_W = -0.0646M_S^2 + 2.0318\ M_S - 4.1368 \qquad \text{Equation (3.2)}$$

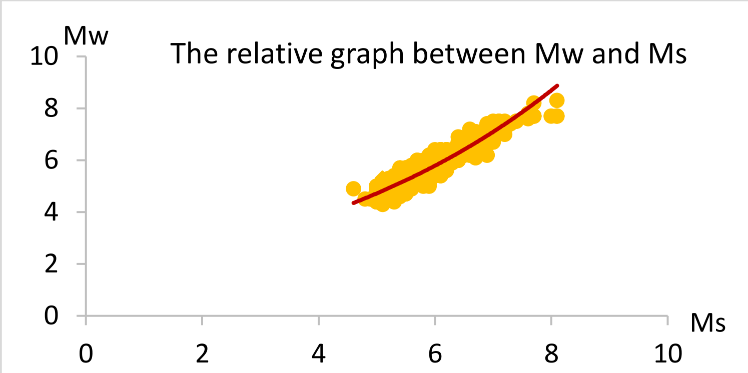


Figure 3.4. The relative graph between M_w and M_S, which the blue is the data in M_S and M_w.

3.2.3. Body-wave magnitude (m_b) and local magnitude (M_L)

The Equation 3.3 is relative between body-wave magnitude (m_b) and local. (M_L) which can be analyzed to relative graph in Figure 3.5.

$$m_b = 0.1089\ M_L^2 - 0.0911M_L + 2.5427 \qquad \text{Equation (3.3)}$$

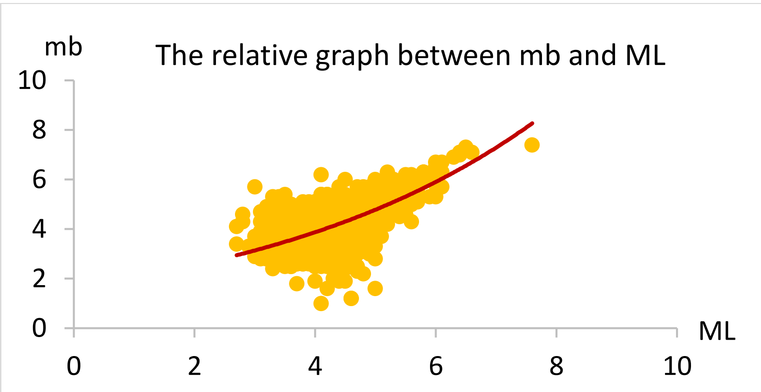


Figure 3.5. The relative graph between m_b and M_L, which the blue is the data in m_b and M_L.

There are two Equations that can directly convert m_b and M_S to M_W (Equations 3.1 and 3.2) While M_L cannot be directly converted to M_W. First, they have to convert M_L to m_b (Equation 3.3). Then m_b is converted to M_W (Equation 3.1). That is finish magnitude conversion.

3.3. Earthquake De-Clustering

In general, the earthquake event consists of foreshock, main shock and aftershock. The main shocks are caused by a stress of crust, directly from tectonic activity whereas foreshocks and aftershocks are caused by releasing energy from a strain. The foreshocks are the energy release from preparation before the main shock occurs. The aftershocks come from the fault movement that adjusts the area back to balance after the main shocks occur. Hence, the foreshocks present low b value, on the other hand, the aftershocks show large b value (Suyehiro et al.,1964).

Therefore, the earthquake event that can genuinely indicate earthquake's behavior is the main shock. However, the data from the international database have all foreshock, main shock and aftershock. So, the main purpose of earthquake de-clustering is to eliminate foreshock and aftershock data, to get the best possible estimate for the rate of mainshocks, by the relative between these following.

1. Magnitude of earthquake
2. Distant of earthquake
3. Time of earthquake event

There are several ways of earthquake de-clustering. However, in this presentation, we accepted the explanation of Gardner and Knopoff (1974). They provided the method known as a window method which is one of the simplest forms of aftershock identification.

The main idea is if the main shocks are small, the vulnerable area that caused by foreshock and aftershock would be small and the time interval of the earthquake event would be short. In the other hand, the vulnerability would be covered the large area and the time interval of aftershock would be long because the adjustment of balance would spend more time.

After earthquake de-clustering, the data remain only the main shock which is 28,733 events in 1964-2016. The magnitude is between 0 -8.1 M_W with depth 0 – 722.5 km (Figure 3.6).

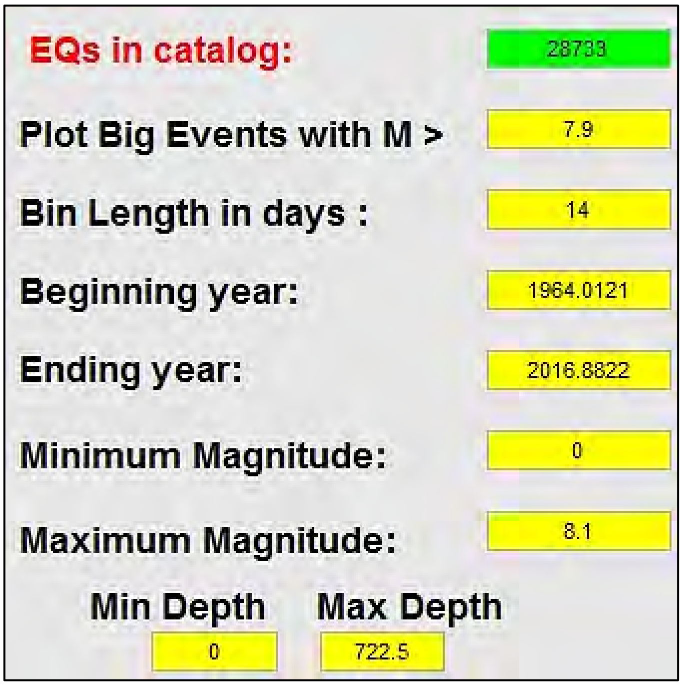


Figure 3.6. Summarize of seismicity data after earthquake de-clustering that remove foreshock and mainshock.

3.4. Man-Made Seismicity

In theory, the seismologist believed that the main factor of tectonic activity that causes an earthquake, such as velocity or movement of crust, cannot change immediately in the short time. Therefore, the rate of earthquake occurrence in the past 100 year should be constant rate. That means the relative between cumulative number event and time should be linear graph.

After considering the graphs between the unrevised data and the de-clustering data in Figure 3.7, we found that the earthquake de-clustering graph was more linear than unrevised data. But it was not the perfect straight line. Thus, we had to improve the data in the next step.

a) Cumulative number of earthquake event (unrevised)

b) Cumulative number of earthquake event (after de-clustering process)

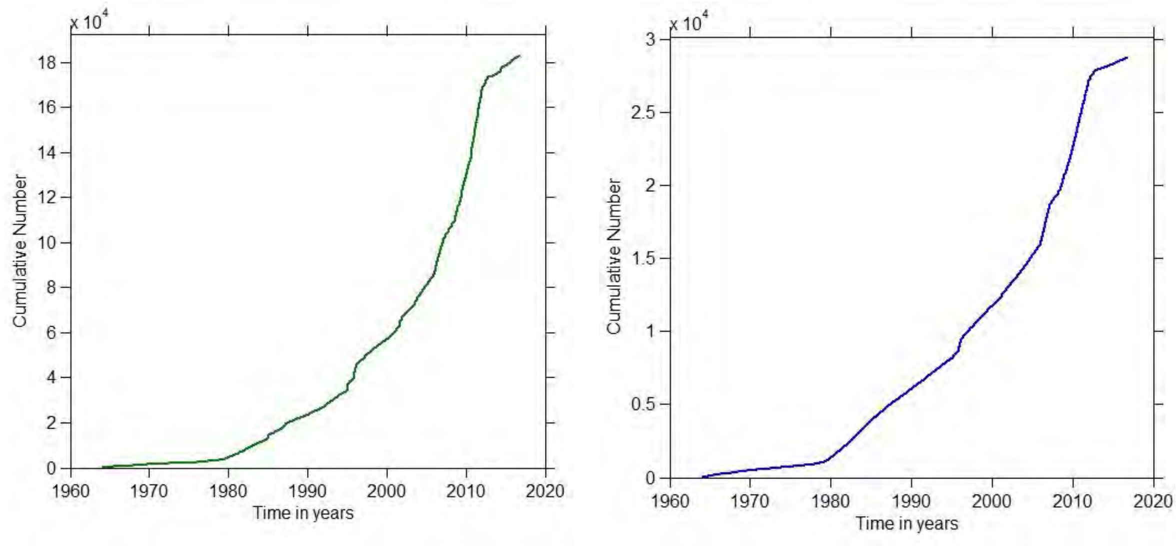


Figure 3.7. The graphs compare between cumulative number of earthquake event between a) unrevised data and b) after earthquake de-clustering.

The seismologists believed that there are the other factors that make the data still not dependent. The past studies identified that the earthquake catalogue is always affected by man-made seismicity. For examples, increases or decreases in the detection and reporting of smaller events which accompany with the installation seismic station (Kanamori, 1981; Habermann and Wyss, 1984; Wyss, 1991).

Changing software for earthquake analysis made all systematic changes in the magnitudes (Wyss and Habermann, 1988), include changes in definition of earthquake (Perez and Scholz, 1984; Habermann, 1987).

Thus, we needed to improve the data catalogue. In this study accepted the method of Habermann (1983; 1987) which provided the seismicity rate changes Equation. It is the relationship between time series and magnitude in Equation (3.4) that we used this formula to cutoff the man-made changes data.

$$Z = \frac{M1 - M2}{\sqrt{\frac{S1^2}{N1} + \frac{S2^2}{N2}}}$$ Equation (3.4)

Z is the seismicity rate changes while M_1 and M_2 are the mean rates in period 1 and 2 respectively. S_1 and S_2 are standard deviation in these periods, where the number of events represents by N_1 and N_2.

When we removed the man-made seismicity, the data remained 19,012 events in 1978-2012. The magnitudes are between 3.3 – 8.1 M_W (Figure 3.8). Then the relative graph was plotted to check the data completion. We found that the cumulative number event graph was more linear (Figure 3.9). That means the earthquake data was more complete.

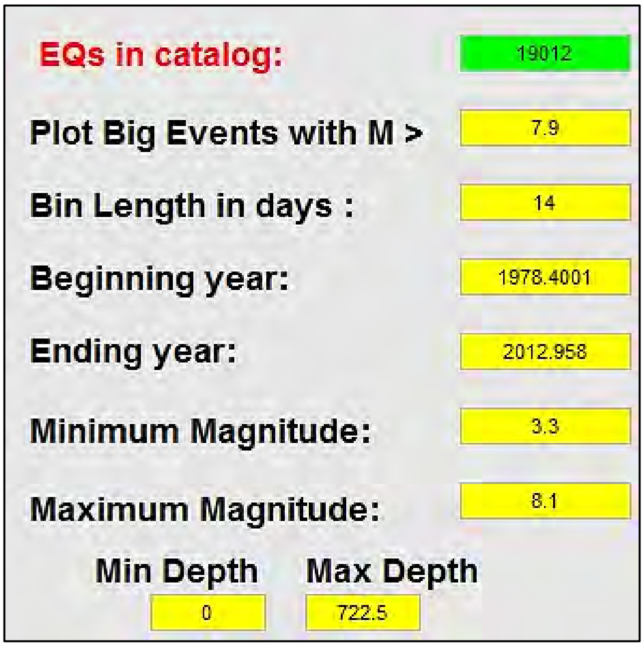
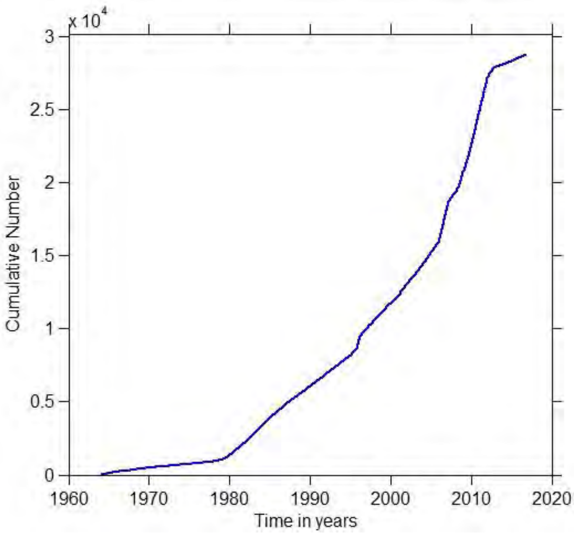


Figure 3.8. Figure showing the earthquake catalogue after eliminated man-made seismicity.

a) Cumulative number of earthquake event (after earthquake declustering)



b) Cumulative number of earthquake event (after man-made seismicity)

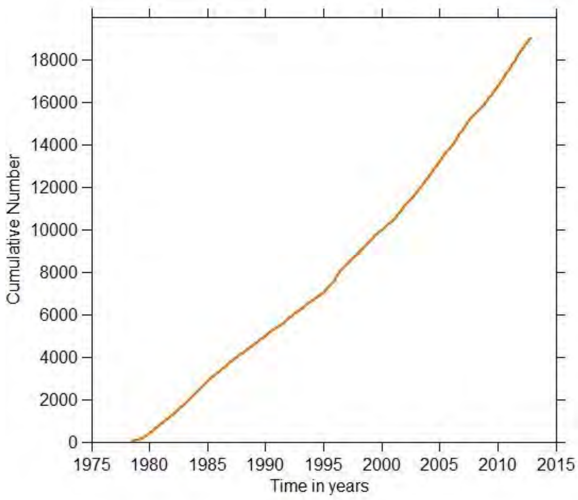


Figure 3.9. The graphs compare between cumulative number of earthquake event a) after earthquake de-clustering and b) man-made seismicity.

3.5. Magnitude of Completeness

From the past studies, seismologist found that the error of data came from the efficiency of instrument record. For example, the small earthquake with slightly shaking cannot be received by the instrument record.

Therefore, Woessner and Wiemer (2005) defined the least magnitude that can be recorded completely called Magnitude of completeness or Mc. That means Mc is the least magnitude that every network can receive correctly value. While some of small earthquake that have magnitude less than Mc cannot be record. It is important to select the suitable Mc to analyze b values accurate and reliable.

After analyze the earthquake catalogue to select the least completeness of magnitude, magnitude and cumulative number events were plotted. In this study, we found that Mc = 4.0 in Figure 3.10. That means the data that used to analyze in the next step must have the magnitude more than 4.0 M_W.

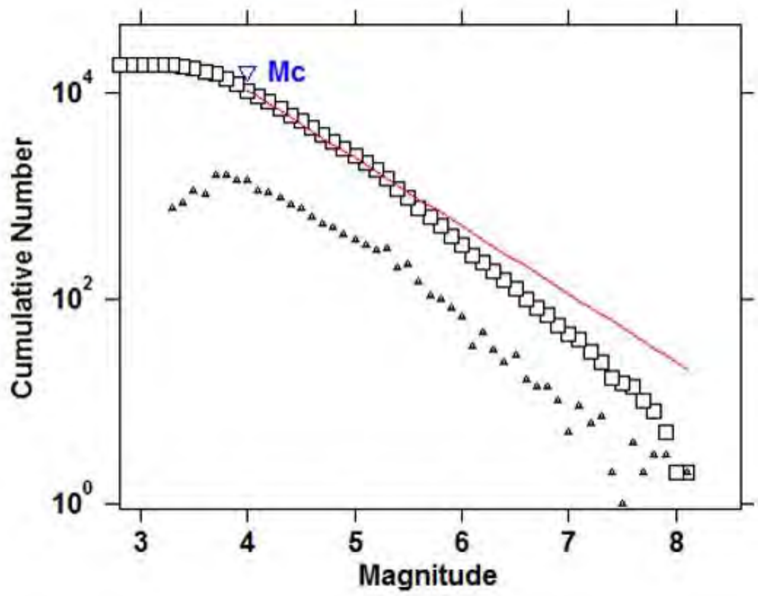


Figure 3.10. The graph shows a typical frequency magnitude of this study. The red line shows that the magnitude of completeness Mc is 4.0.

After we revised the earthquake data through all the following statistic processes. We got the complete data that can genuinely indicate the earthquake behavior and accuracy result. The data remained 10,651 events in 1978 – 2012 which the magnitude was between 4.0 – 8.1 M_W in Figure 3.11.

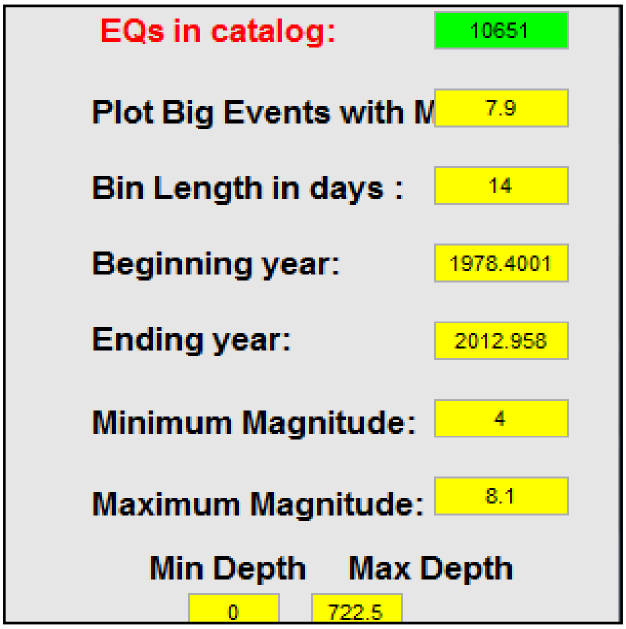


Figure 3.11. Figure shows the data after selecting magnitude of completeness which Mc = 4.0.

Earthquake data (unrevised) After earthquake de-clustering After man-made seismic removing

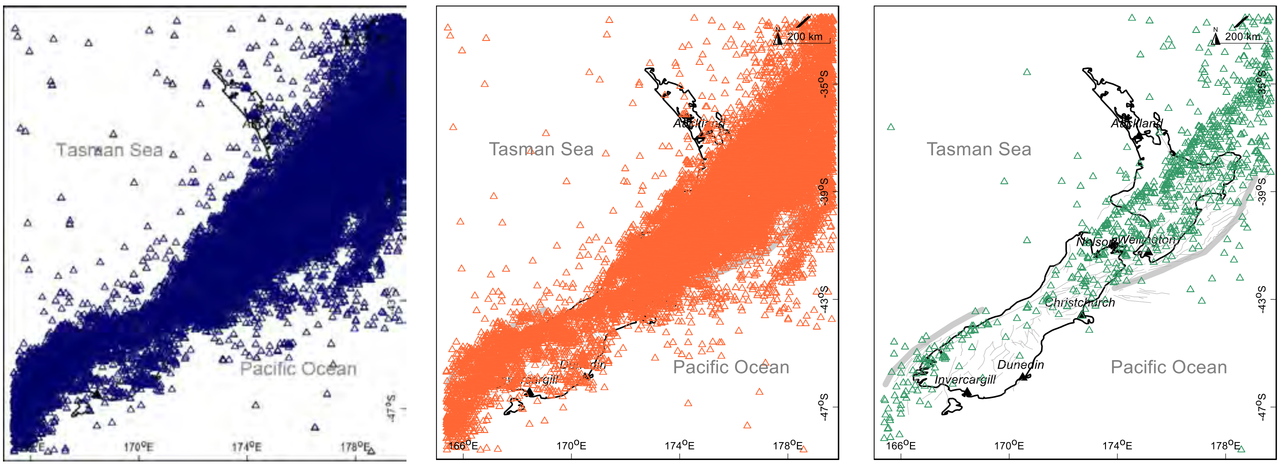


Figure 3.12. showed the distribution of earthquake data a) unrevised b) after de-clustering and c) after seismic man-made removing.

CHAPTER IV

ANALYSIS AND RESULT

4.1. Retrospective Test

Retrospective Test is to look backwards at the events and examines for factors in relation to an outcome that is established at the start of the study. This term was used in b-value analysis. Started with finding the conditions that the earthquake events occurred from investigating case studies.

4.1.1. Case study

In this study, we considered the large earthquake events that have more than 7.0 M_W. Since we needed to ensure the data can indicate the earthquake behavior genuinely. There are 6 events of case study in Figure 4.1 and describe in Table 4.1.

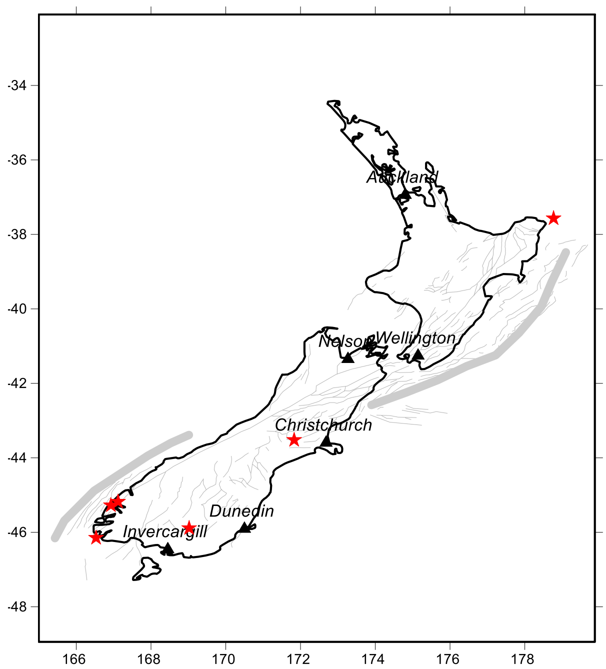


Figure 4.1. The map showing 6 earthquake events (red star) recognized as the case studies.

Table 4.1. The earthquake catalogue of 6 case studies with magnitude ≥ 7.0.

Events	Longitude	Latitude	Year	Month	Day	Magnitude (M_W)	Depth (km)	Hour	Minute
1	166.927	-45.277	1993	8	10	7	36	0	51
2	178.77	-37.57	1995	2	5	7.3	61	22	51
3	167.12	-45.18	2003	8	21	7.7	33	12	12
4	169.02	-45.89	2007	10	15	7.2	33	12	29
5	166.53	-46.15	2009	7	15	7.9	31.5	9	22
6	171.83	-43.522	2010	9	3	7.1	12	16	35

4.1.2 Mapping b value

Once we had the earthquake catalogue, we can calculate b values for selected cross section by using ZMAP developed by Wiemer (2001). ZMAP was programmed in the Matlab scripts. It requires the area of study to be divided into a grid. At each node, the Mc and the b value were computed from the N closest events to the node, which N is a fixed number. Then it computes b values which uses the maximum likelihood method by Aki, K (1965). Also, calculates the standard deviation and goodness fit to power map to ensure the accuracy of result.

In order to computed b values which are temporal changes, we had to find the appropriate conditions to calculate b values of New Zealand region, which we fixed the number of events in any radius. The number of sample had been changed from 30 to 70 events (i.e., at 30, 40, 50, 60, and 70) respectively to find the suitable number for detecting more stability of results. By this method, the radius varies with the earthquake density while the number of events is fixed.

Map resolution depends on the grid nodes and earthquake density (Nuannin et al., 2006). In the other word, a map with a high density of earthquakes and small grid spacing will present a high resolution. Thus, the study area was separated into a grid of 0.25 x 0.25°, N_{min} was set to 5 to avoid too many gaps. The study area was divided into 3648 nodes. We calculated each area by changing the radii following the number of events we fixed.

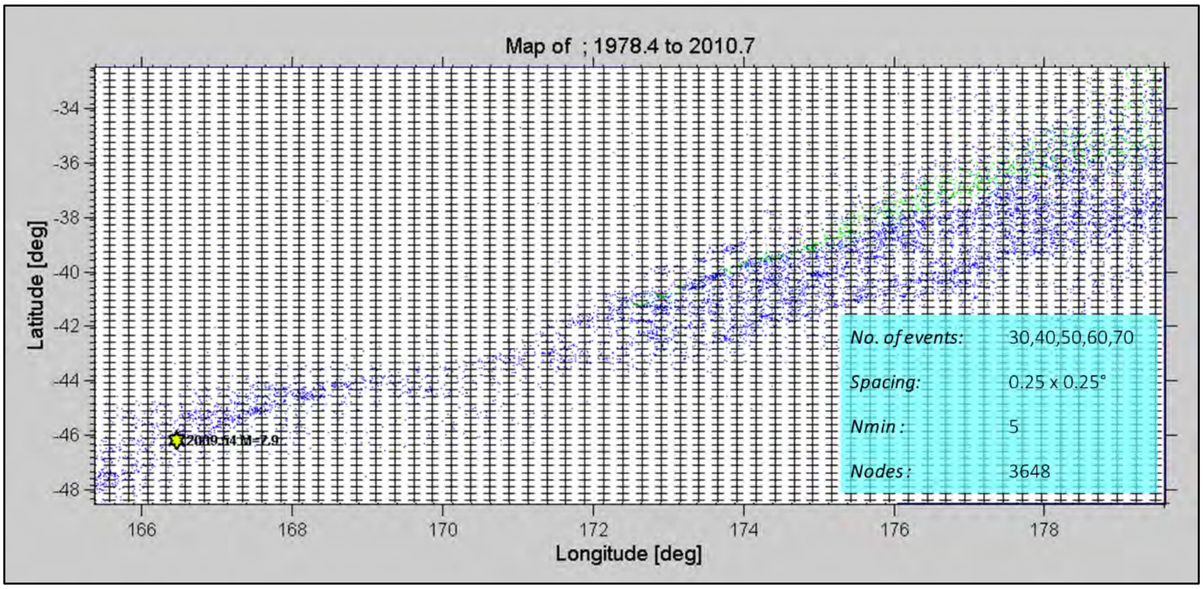
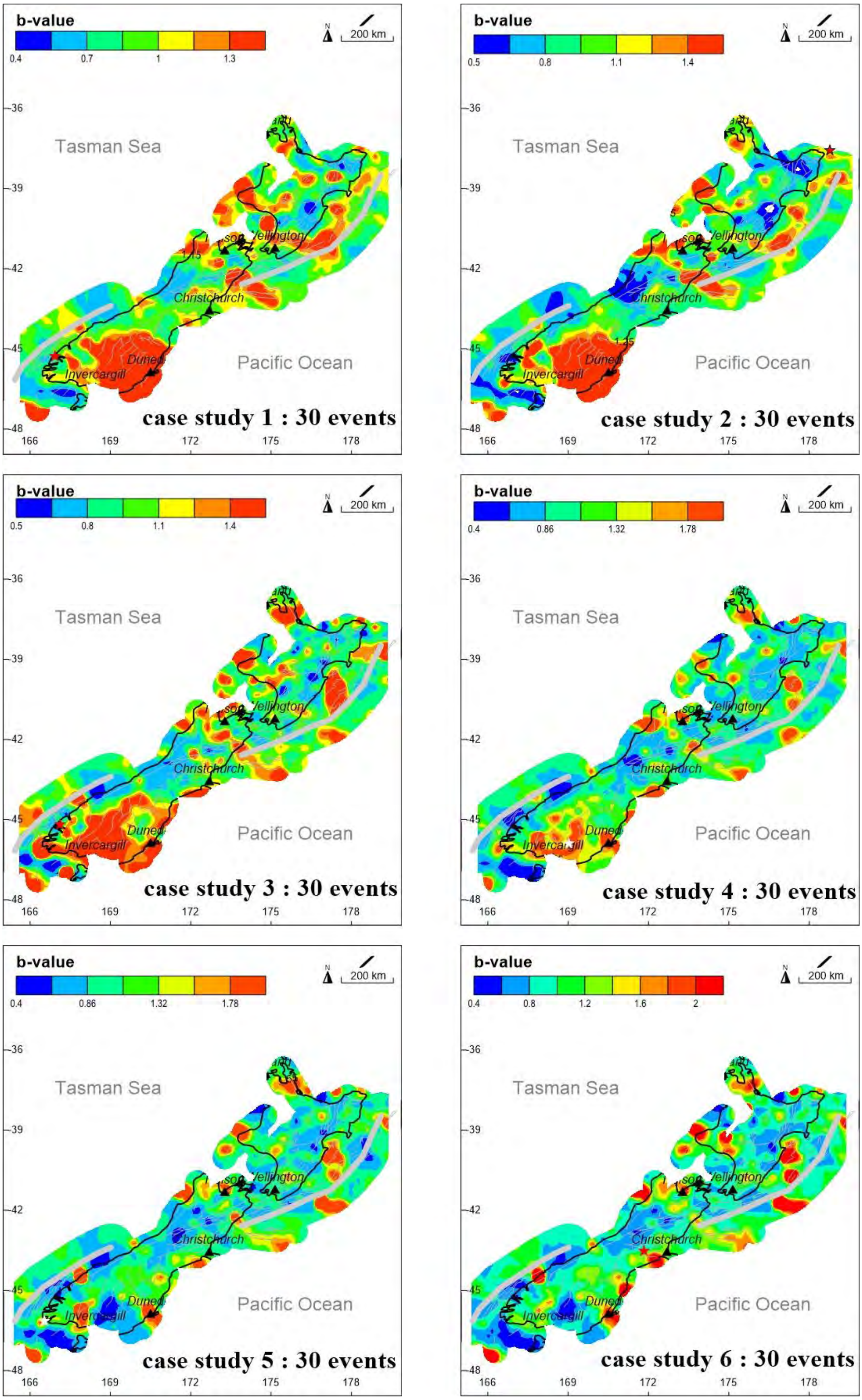
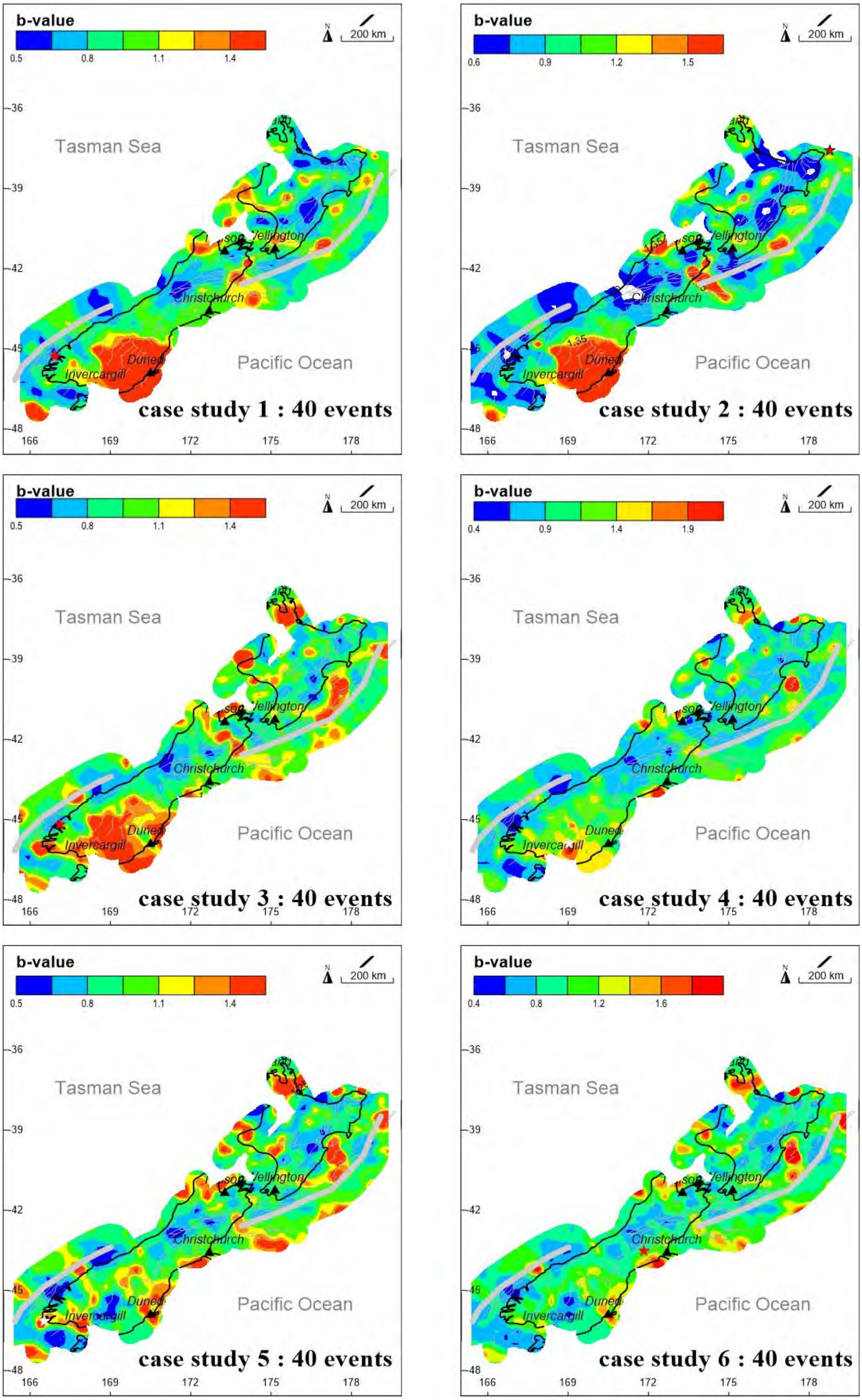


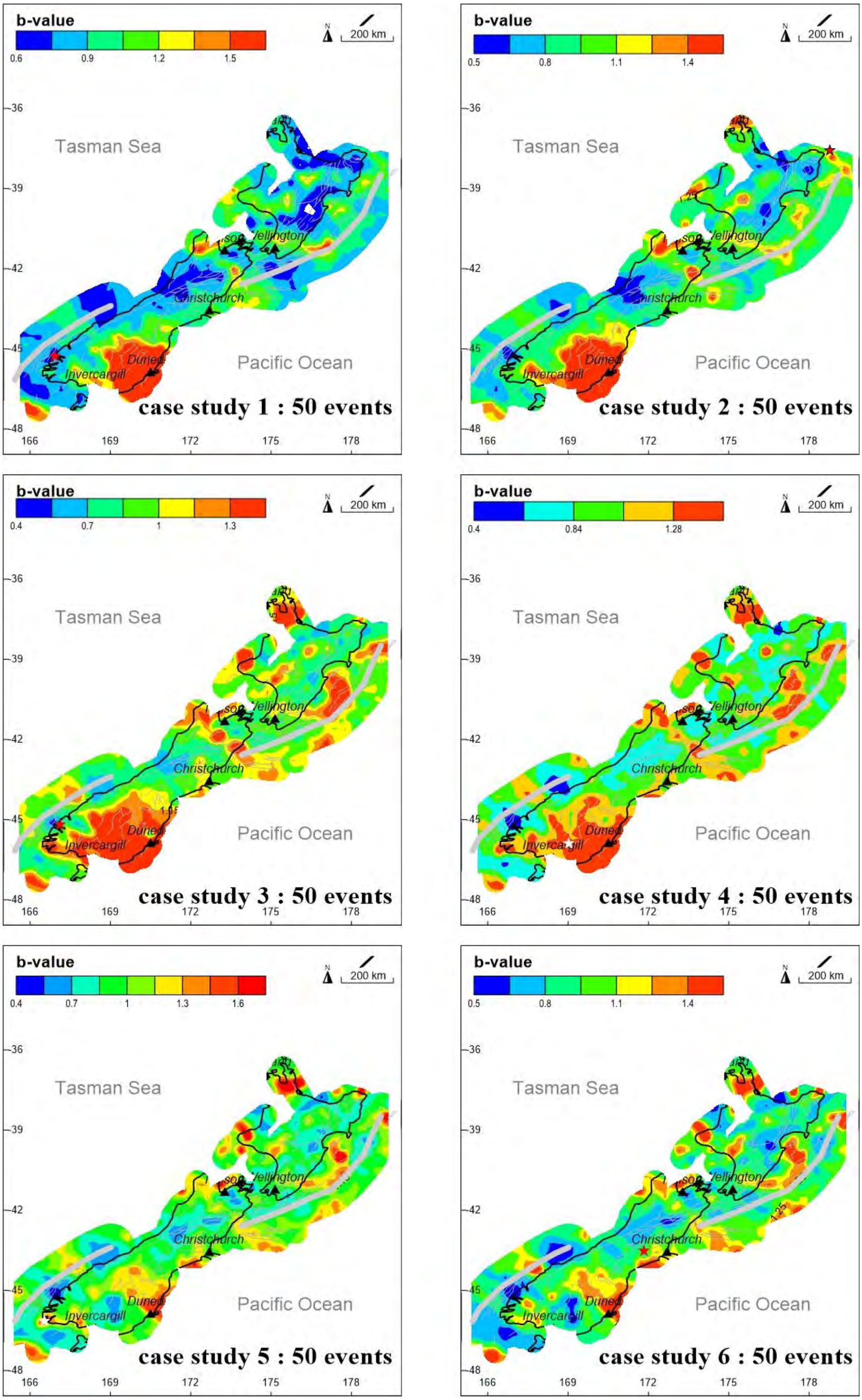
Figure 4.2. The study area was divided into 3648 nodes, by a grid of 0.25 x 0.25°.

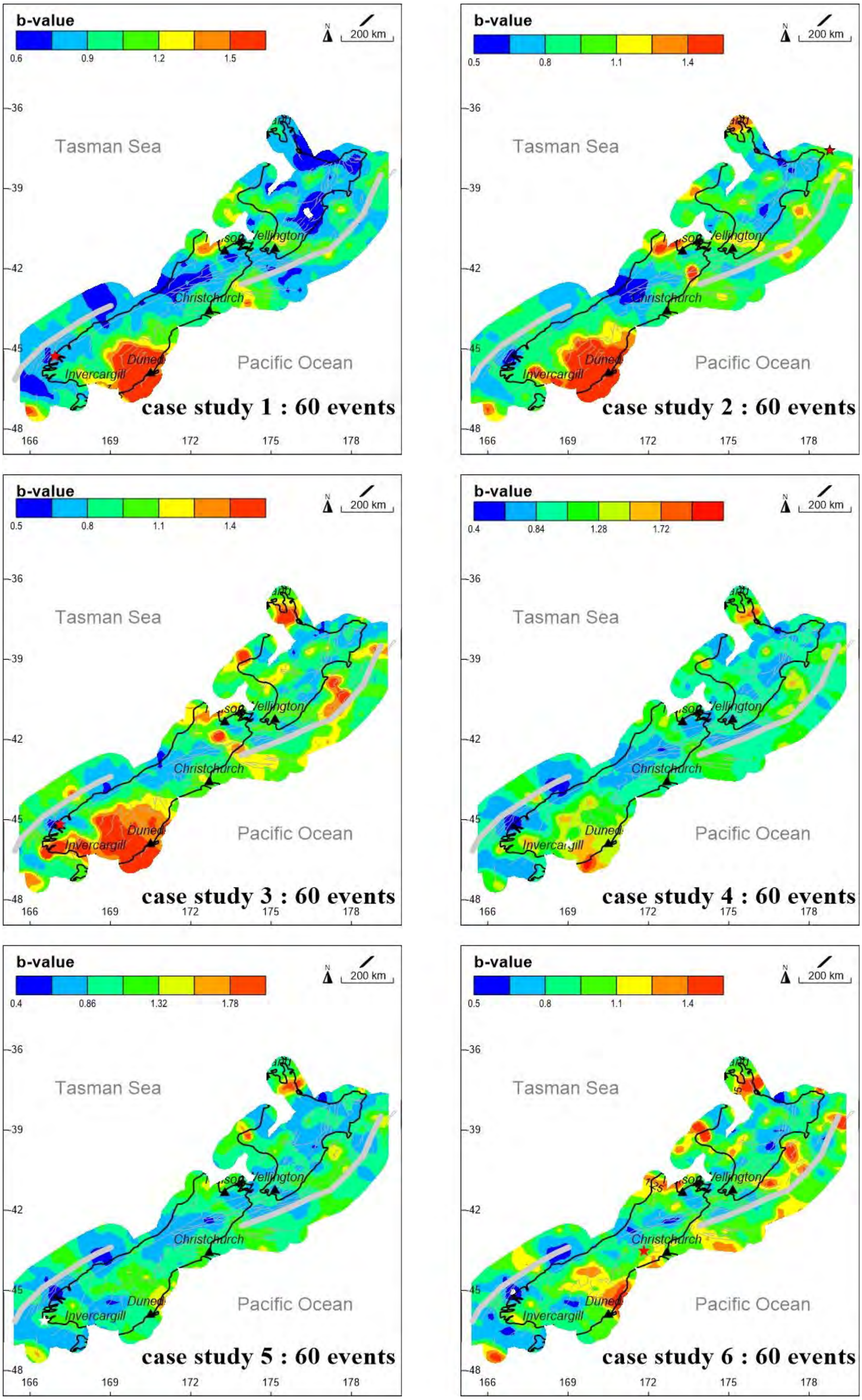
Then, we got the cumulative number of events and magnitude plotted the frequency-magnitude distribution. The relation between two factors would be linear graph. According to Gutenberg-Richter relation, we can estimate b value from the slope. Then, the b-value estimated at each node is translated into a color code to find anomalies (low b values). Finally, we mapped the spatial distribution of b values (Figure 4.3). We computed and mapped the goodness fit to power law to ensure the accuracy of data (Figure 4.4). Also, we calculated the standard deviation to find the error of each cases study (Figure 4.5) and a value map (Figure4.6) by using Surfer v.11.


b-value
0.4
0.7
1
1.3
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 1 : 30 events
b-value
0.5
0.8
1.1
1.4
200 km
Tasman Sea
Pacific Ocean
case study 2 : 30 events
b-value
0.5
0.8
1.1
1.4
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 3 : 30 events
b-value
0.4
0.86
1.32
1.78
200 km
Tasman Sea
Pacific Ocean
case study 4 : 30 events
b-value
0.4
0.86
1.32
1.78
200 km
Tasman Sea
Pacific Ocean
case study 5 : 30 events
b-value
0.4
0.8
1.2
1.6
2
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 6 : 30 events
-36
-39
-42
-45
-48
166
169
172
175
178



b-value
0.5 0.8 1.1 1.4
200 km
Tasman Sea
Christchurch
Invercargill
Pacific Ocean
case study 1 : 40 events
b-value
0.6 0.9 1.2 1.5
200 km
Tasman Sea
Christchurch
Invercargill
Pacific Ocean
case study 2 : 40 events
b-value
0.5 0.8 1.1 1.4
200 km
Tasman Sea
Christchurch
Invercargill
Pacific Ocean
case study 3 : 40 events
b-value
0.4 0.9 1.4 1.9
200 km
Tasman Sea
Christchurch
Pacific Ocean
case study 4 : 40 events
b-value
0.5 0.8 1.1 1.4
200 km
Tasman Sea
Christchurch
Invercargill
Pacific Ocean
case study 5 : 40 events
b-value
0.4 0.8 1.2 1.6
200 km
Tasman Sea
Christchurch
Invercargill
Pacific Ocean
case study 6 : 40 events


b-value
0.6 0.9 1.2 1.5
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 1 : 50 events
b-value
0.5 0.8 1.1 1.4
200 km
Tasman Sea
Pacific Ocean
Invercargill
case study 2 : 50 events
b-value
0.4 0.7 1 1.3
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 3 : 50 events
b-value
0.4 0.84 1.28
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 4 : 50 events
b-value
0.4 0.7 1 1.3 1.6
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 5 : 50 events
b-value
0.5 0.8 1.1 1.4
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 6 : 50 events
-36
-39
-42
-45
-48
166
169
172
175
178


b-value
0.6
0.9
1.2
1.5
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 1 : 60 events
b-value
0.5
0.8
1.1
1.4
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 2 : 60 events
b-value
0.5
0.8
1.1
1.4
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 3 : 60 events
b-value
0.4
0.84
1.28
1.72
200 km
Tasman Sea
Pacific Ocean
Christchurch
case study 4 : 60 events
b-value
0.4
0.86
1.32
1.78
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 5 : 60 events
b-value
0.5
0.8
1.1
1.4
200 km
Tasman Sea
Pacific Ocean
Christchurch
Invercargill
case study 6 : 60 events
-36
-39
-42
-45
-48
166
169
172
175
178

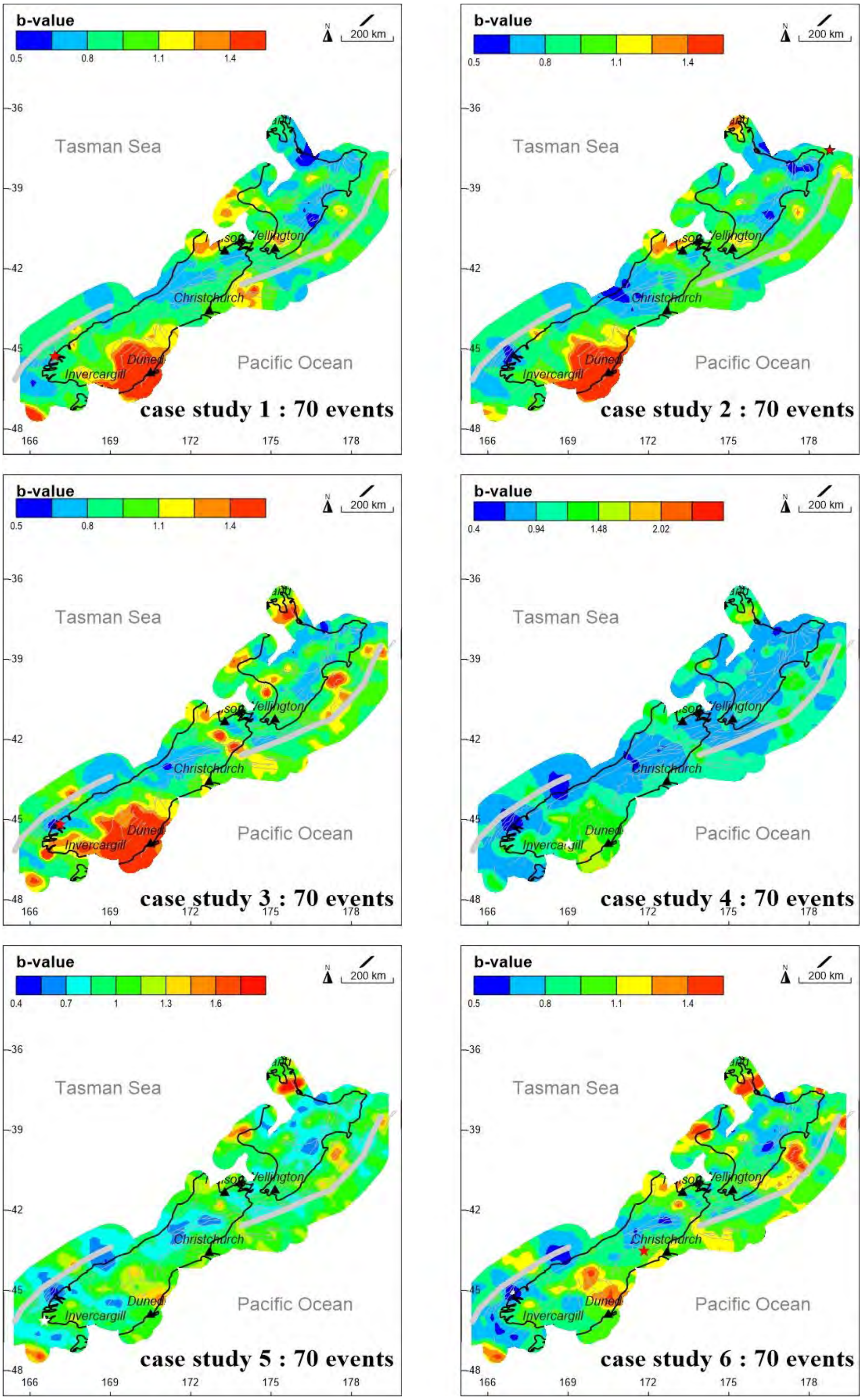
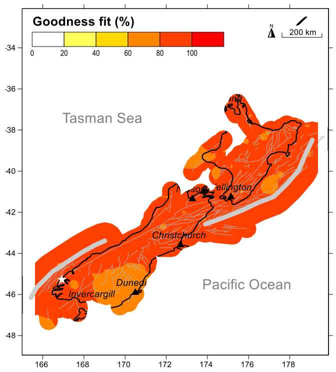
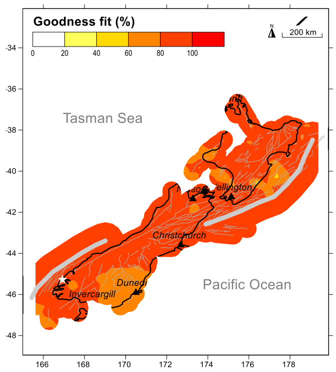


Figure 4.3. Mapping of b value which indicate epicenters (stars) and low b values (blue area).

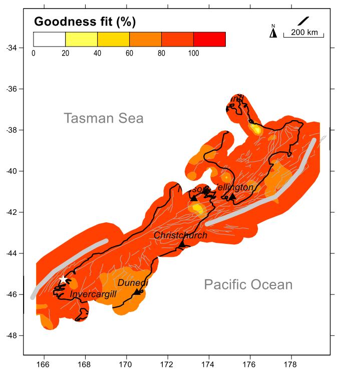
case study 1 : 30 events



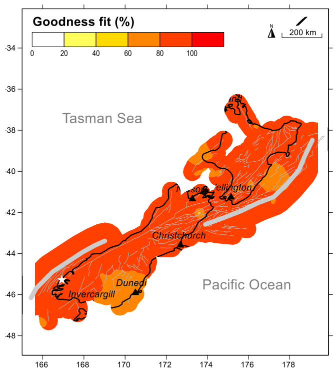
case study 1 : 40 events



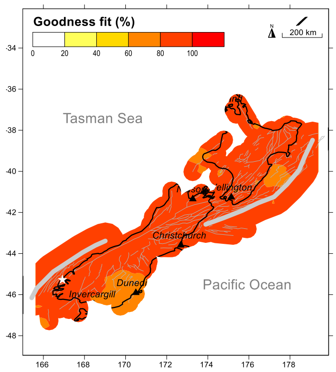
case study 1 : 50 events



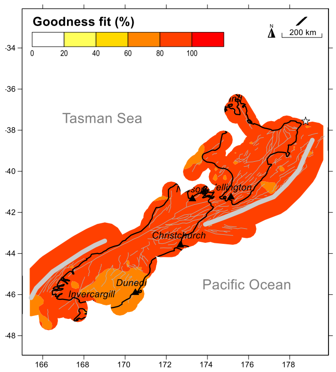
case study 1 : 60 events



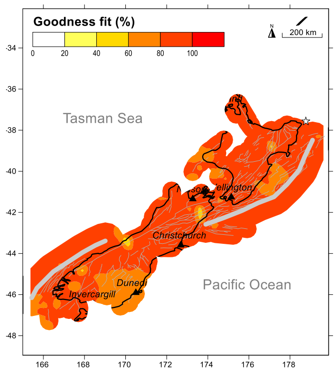
case study 1 : 70 events



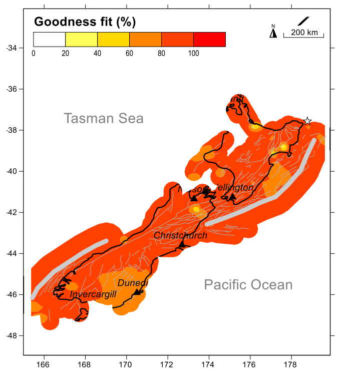
case study 2 : 30 events



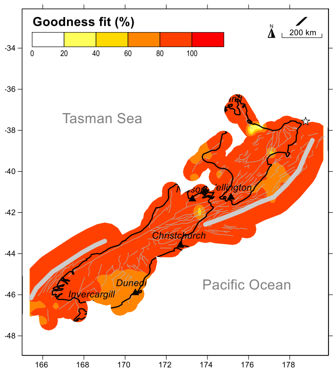
case study 2 : 40 events



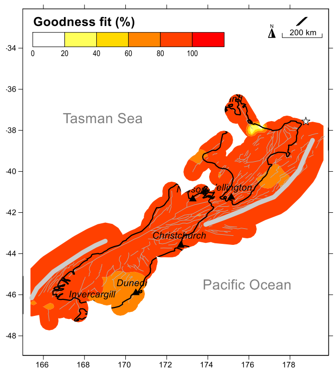
case study 2 : 50 events



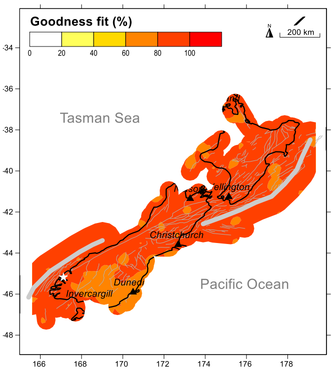
case study 2 : 60 events



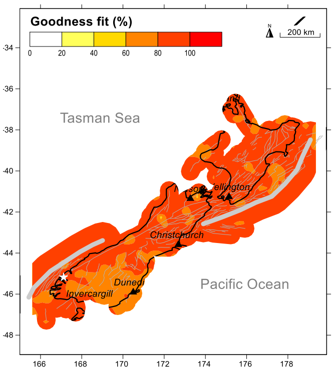
case study 2 : 70 events



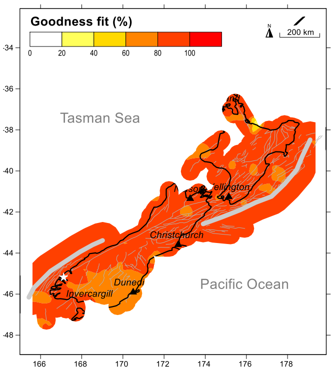
case study 3 : 30 events



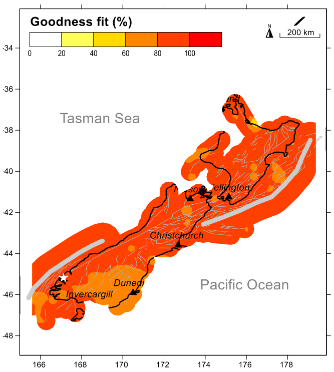
case study 3 : 40 events



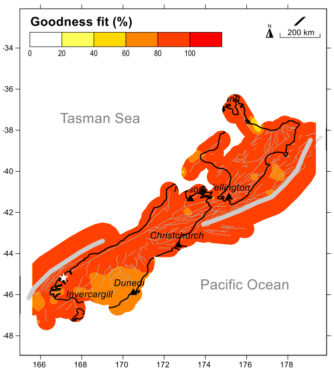
case study 3 : 50 events



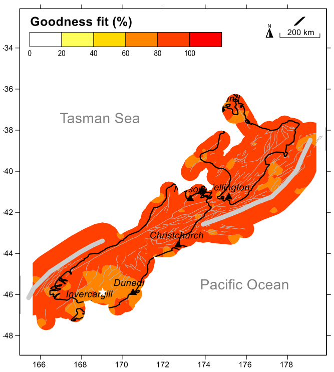
case study 3 : 60 events



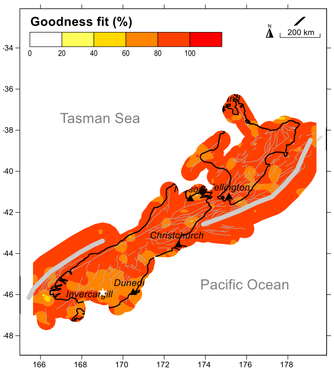
case study 3 : 70 events



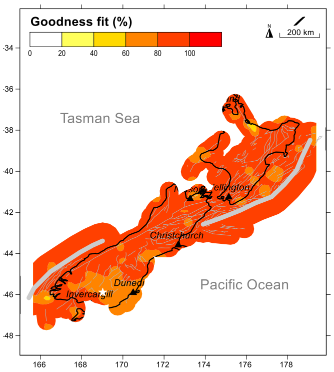
case study 4 : 30 events



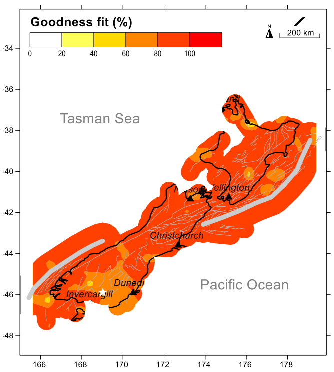
case study 4 : 40 events



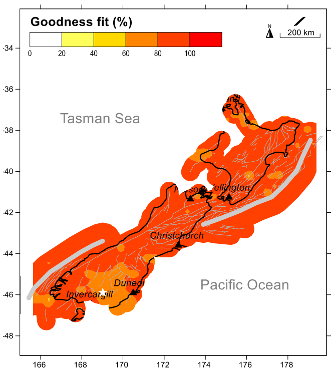
case study 4 : 50 events



case study 4 : 60 events



case study 4 : 70 events



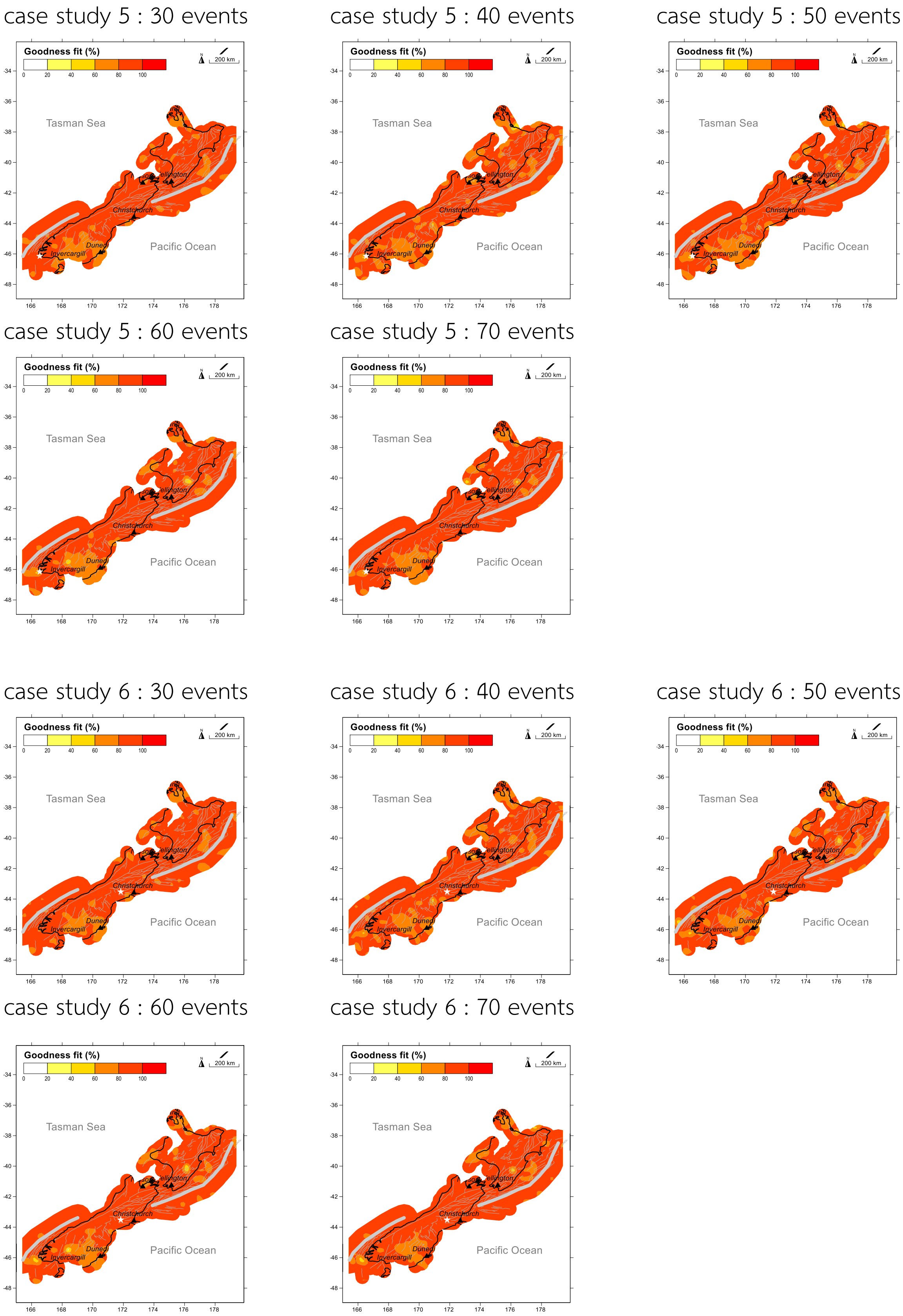
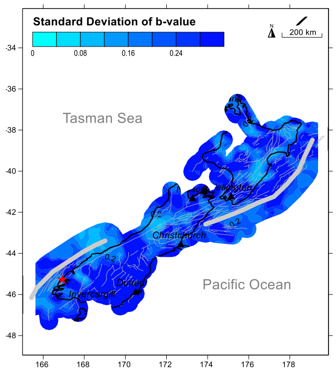
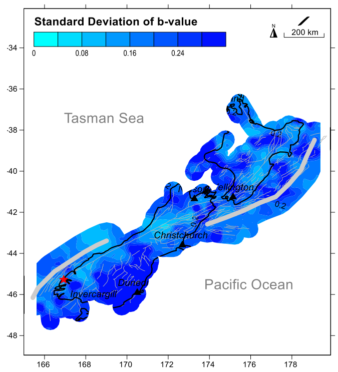


Figure 4.4. Mapping of goodness fit (%) which are close to red means it highly accurate.

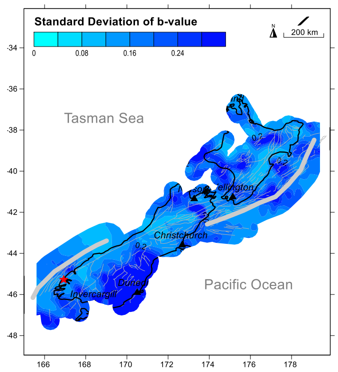
case study 1 : 30 events



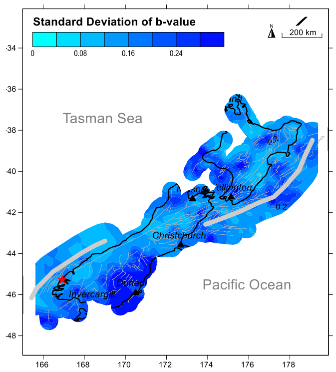
case study 1 : 40 events



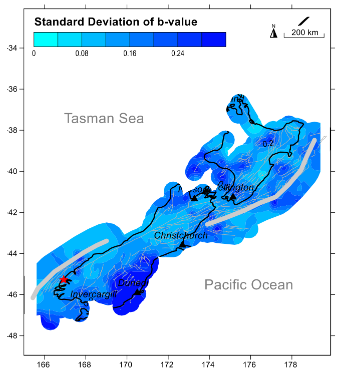
case study 1 : 50 events



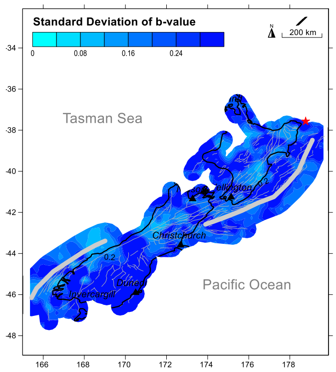
case study 1 : 60 events



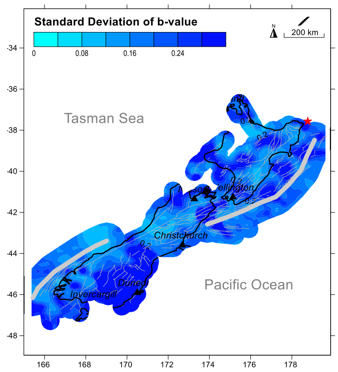
case study 1 : 70 events



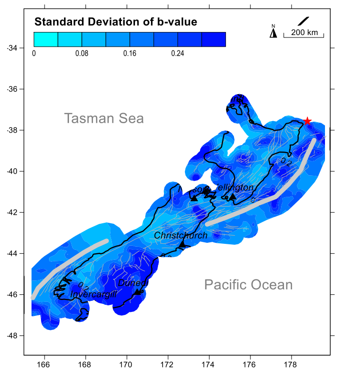
case study 2 : 30 events



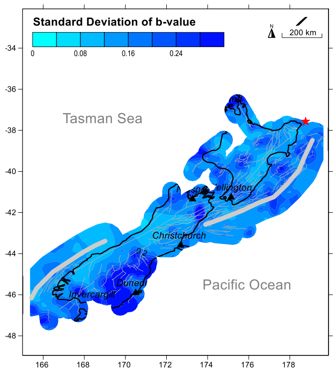
case study 2 : 40 events



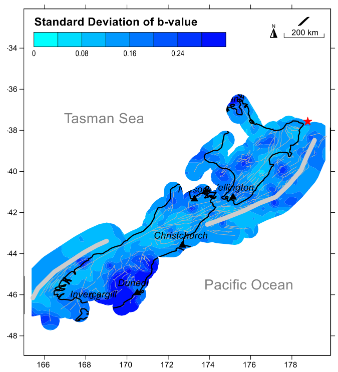
case study 2 : 50 events



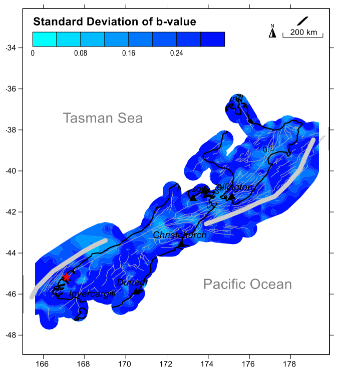
case study 2 : 60 events



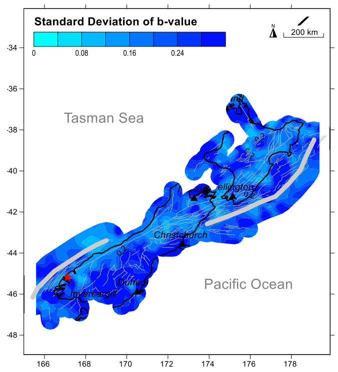
case study 2 : 70 events



case study 3 : 30 events



case study 3 : 40 events



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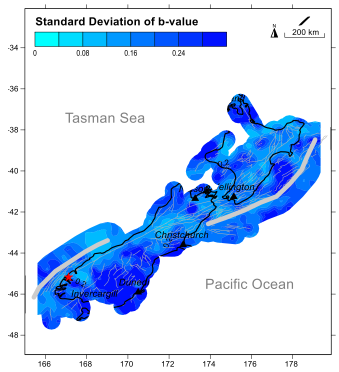

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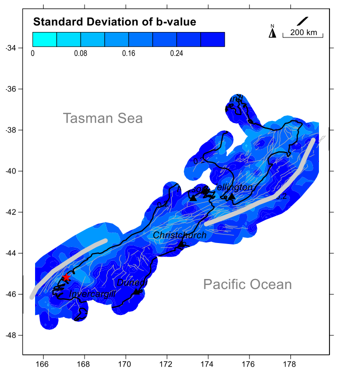

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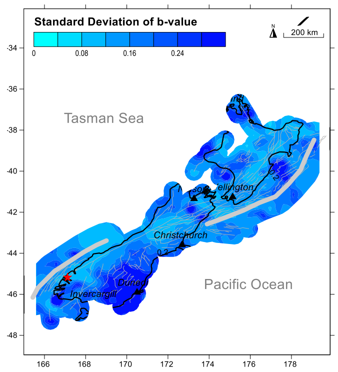

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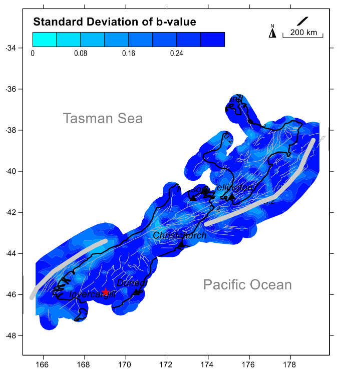

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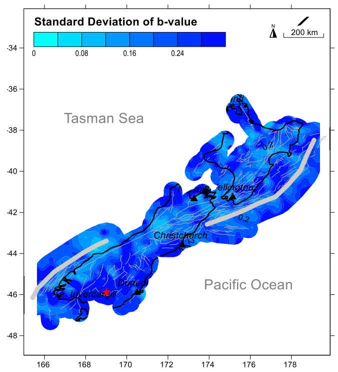
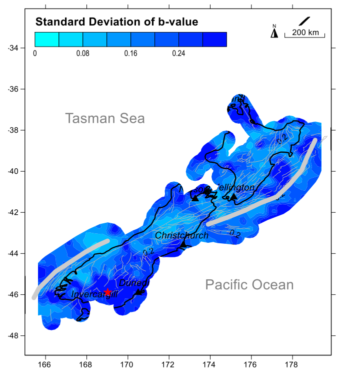


case study 4 : 50 events



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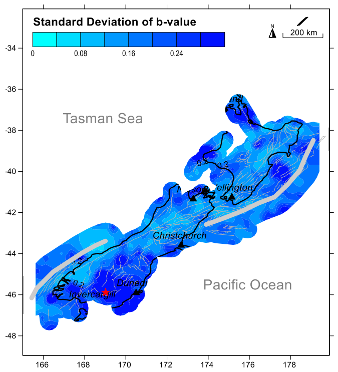
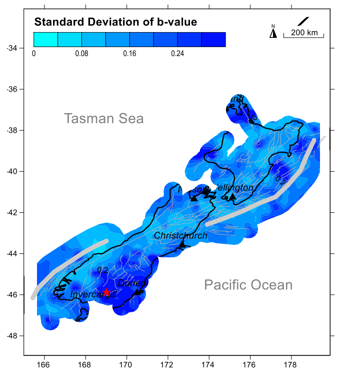


case study 4 : 70 events



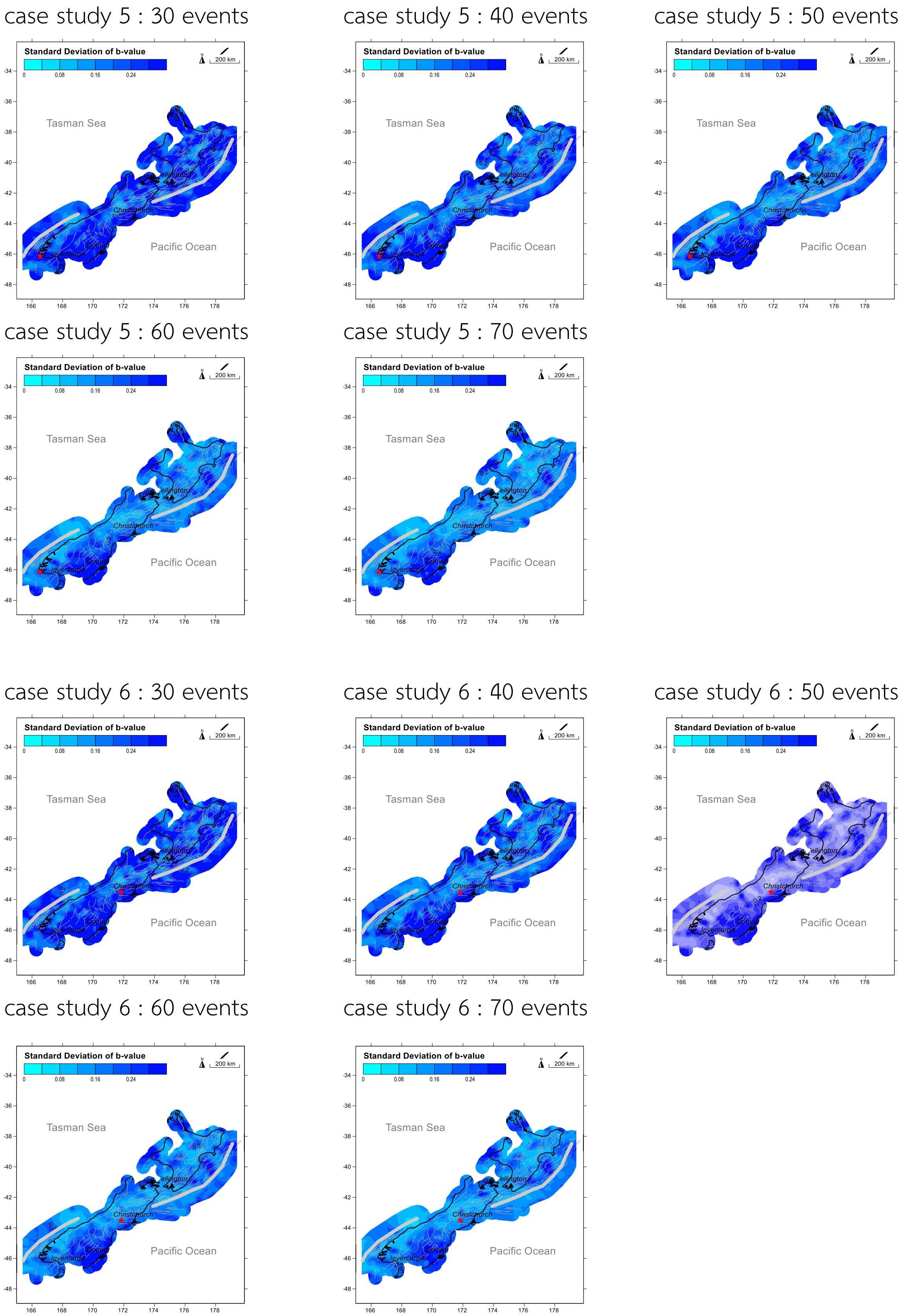
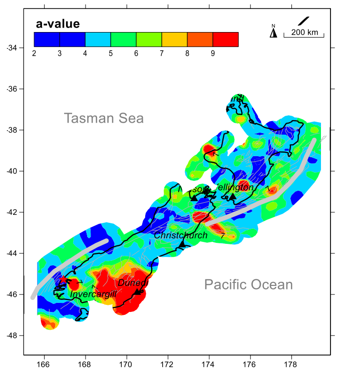
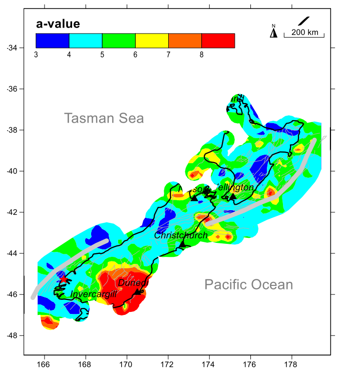


Figure 4.5. Mapping of standard deviation of b value which light blue areas shows less error.

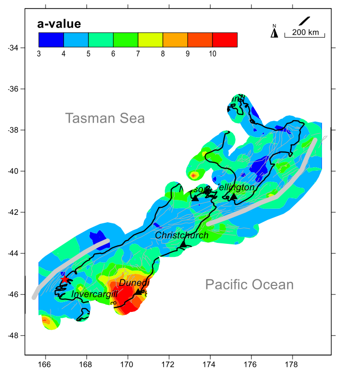
case study 1 : 30 events



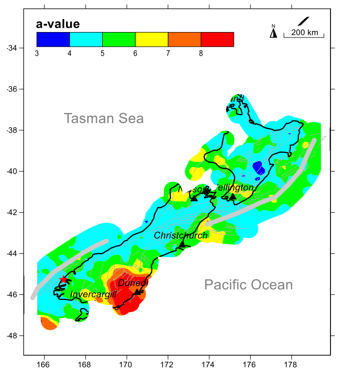
case study 1 : 40 events



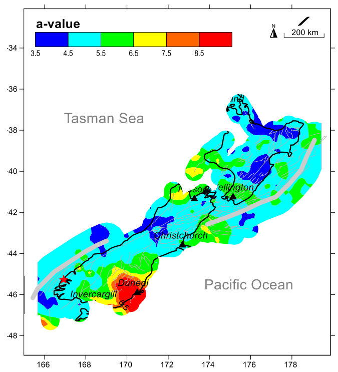
case study 1 : 50 events



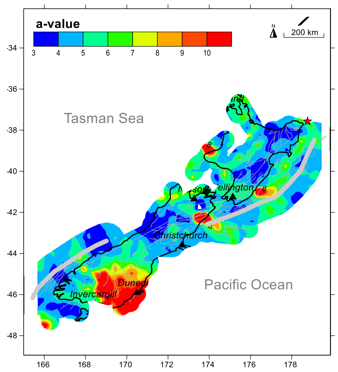
case study 1 : 60 events



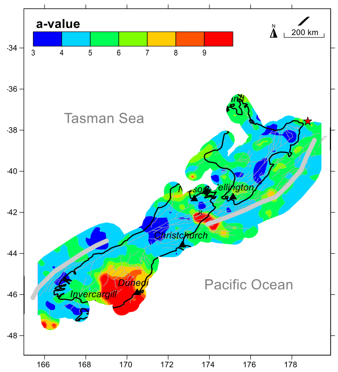
case study 1 : 70 events



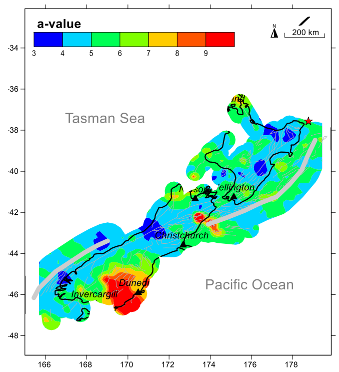
case study 2 : 30 events



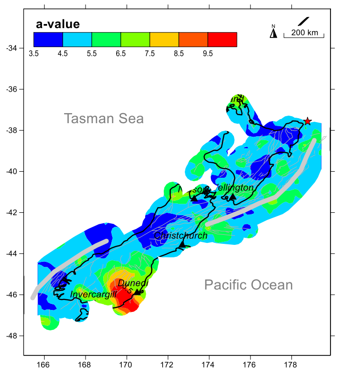
case study 2 : 40 events



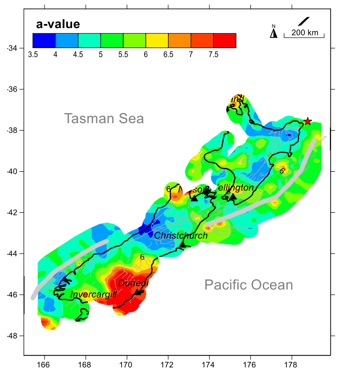
case study 2 : 50 events



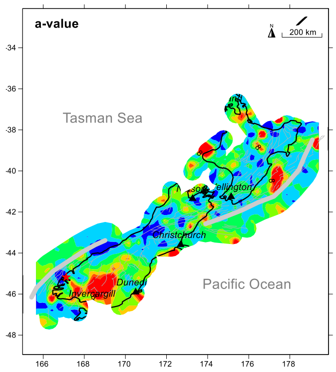
case study 2 : 60 events



case study 2 : 70 events



case study 3 : 30 events



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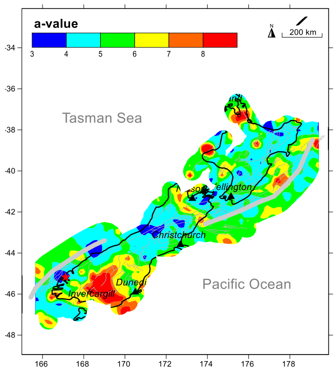
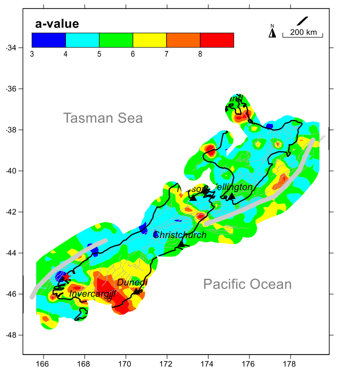
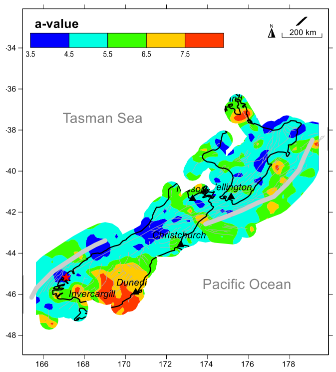


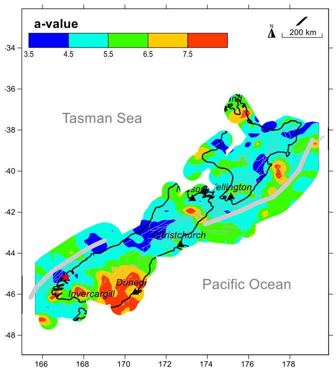
case study 3 : 50 events



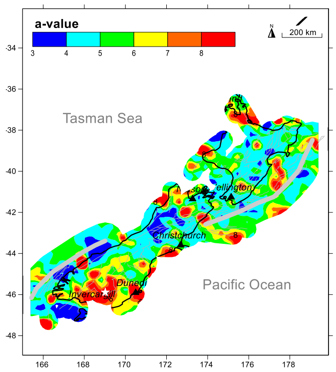
case study 3 : 60 events



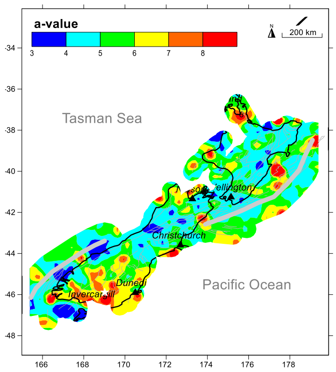
case study 3 : 70 events



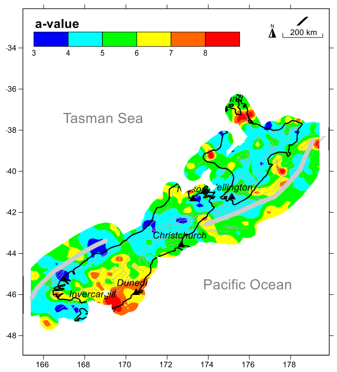
case study 4 : 30 events



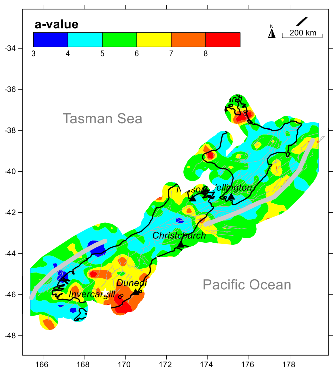
case study 4 : 40 events



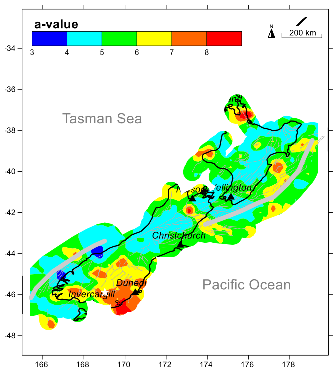
case study 4 : 50 events



case study 4 : 60 events



case study 4 : 70 events



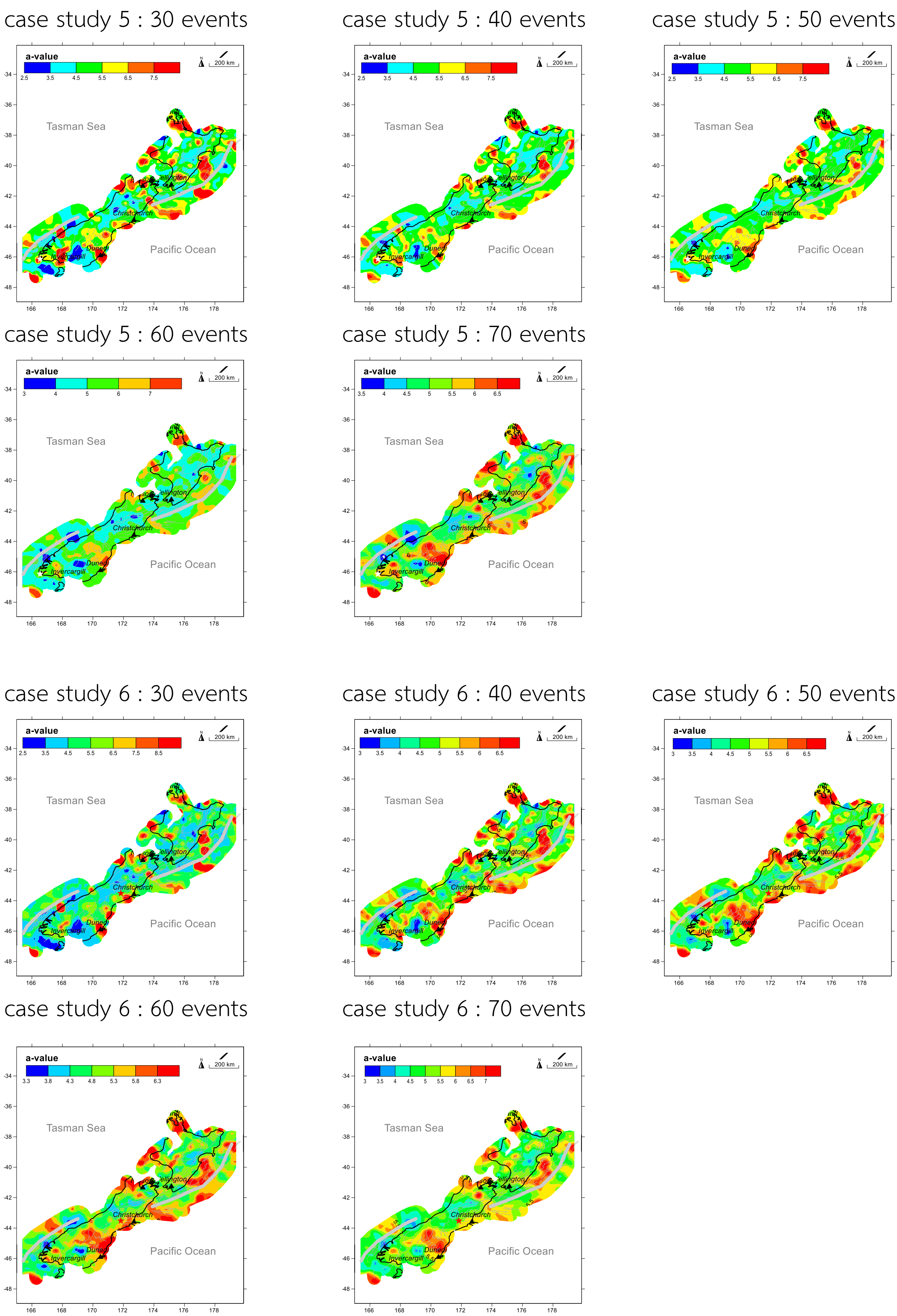


Figure 4.6. Mapping of the spatial distribution of a-value.

From the spatial distribution of the b-value, we found that there are some case studies that not match with the hypocenter, which are case study of 4,5 and 6. However, in the case study of 1,2 and 3 present the b-values match the hypocenter of the past large earthquake (red star on blue area).

4.2. Evaluation of Prospective Area

It was observed that sampling with 50 number of events showed significant result. Thus, we selected 50 events for 0.25 x 0.25 grid nodes covering New Zealand. The b value is computed by using only the earthquakes with magnitude greater than Mc which is 4 M_w. Finally, the spatial changes of b values were considered as an important characteristic of this area. Thus, we can identify the anomalous area of b value.

From January 2011 to December 2012, there are 11 anomalous areas of low b value in Figure 4.7 which are these following.

Southern island

1. Invercargill
2. West of Te Anau and Queenstown
3. South of Queenstown
4. West of Mt. Cook and Franz Josef
5. East of Greymouth and West of Kaikoura
6. Christchurch

Northern island

7. Napier
8. New Plymouth and South of Hamilton
9. Rotorua and Taupo
10. Eastern coast of Wellington
11. Eastern coast of Gisborne

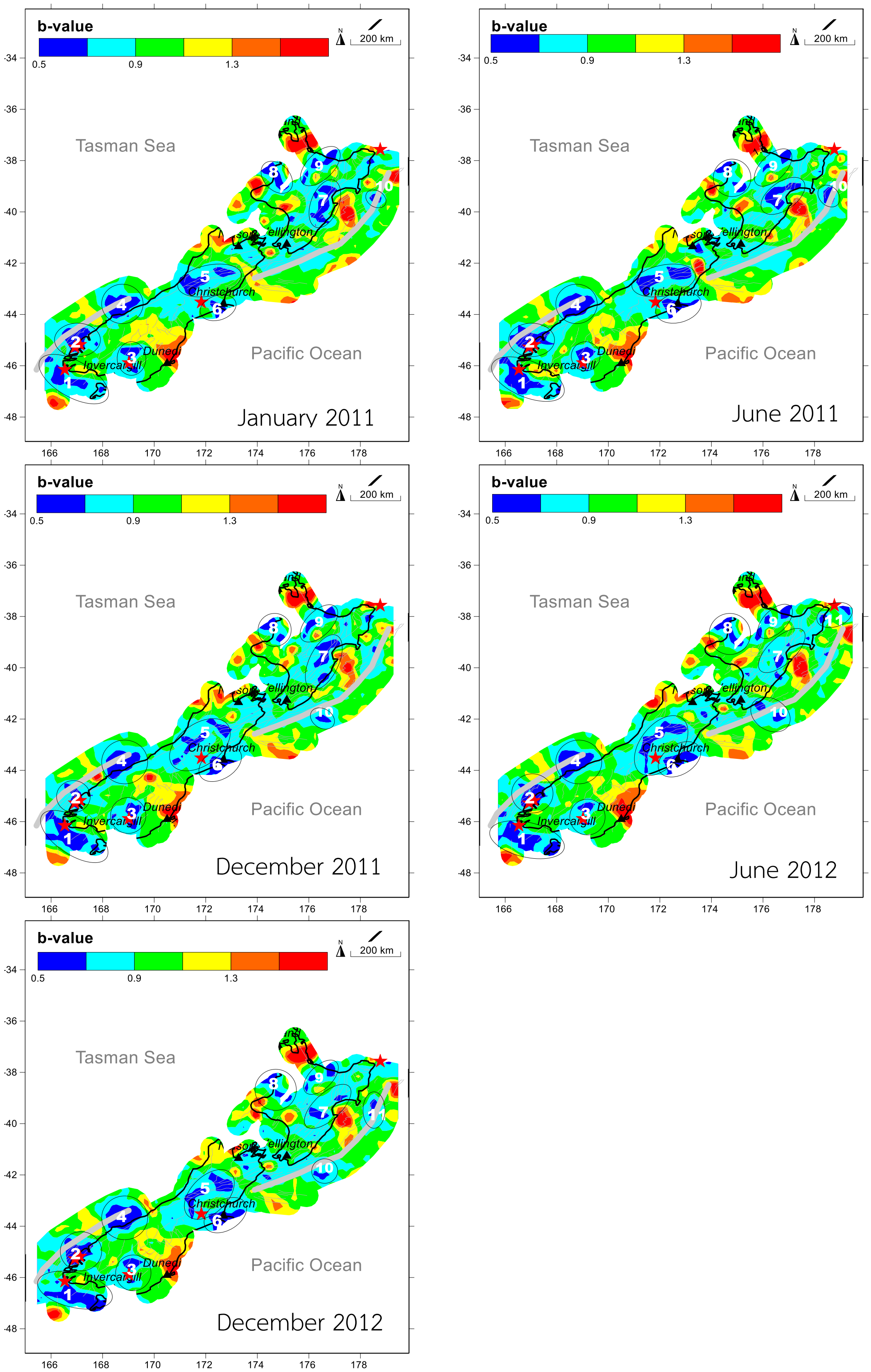


Figure 4.7. The present day spatial distribution of b-values of New Zealand (1964-2012).

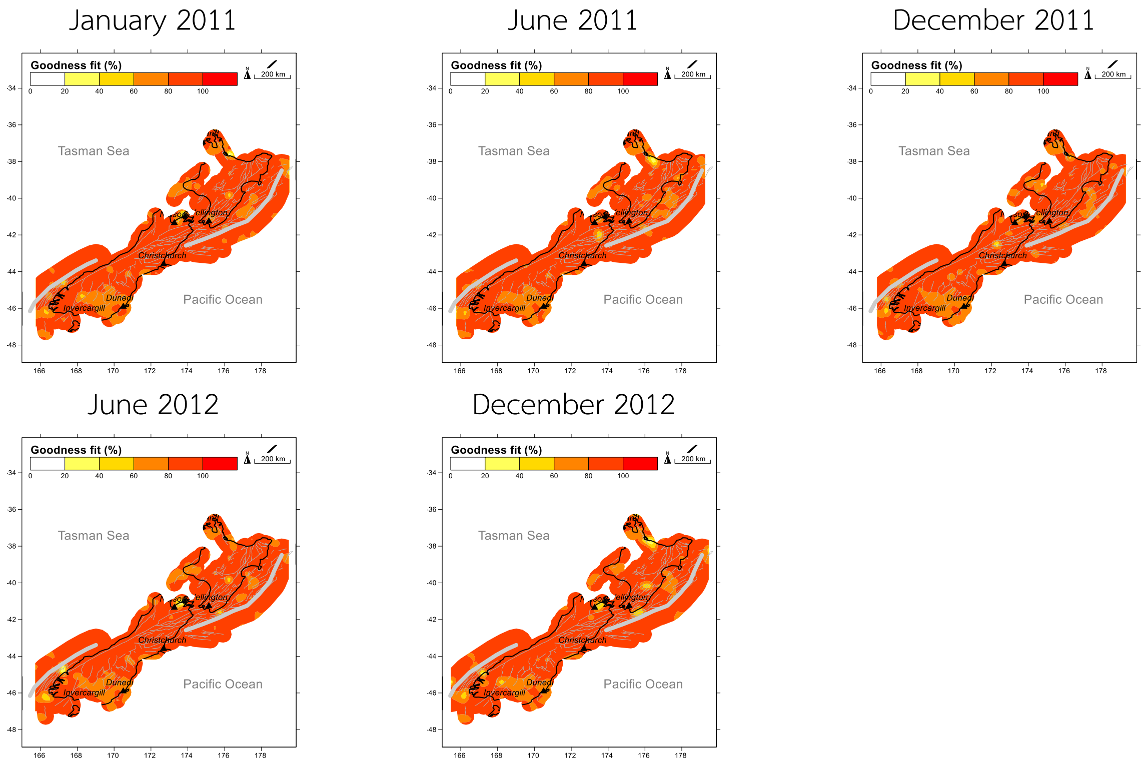


Figure 4.8. Mapping of goodness fit of present day (1964-2012)

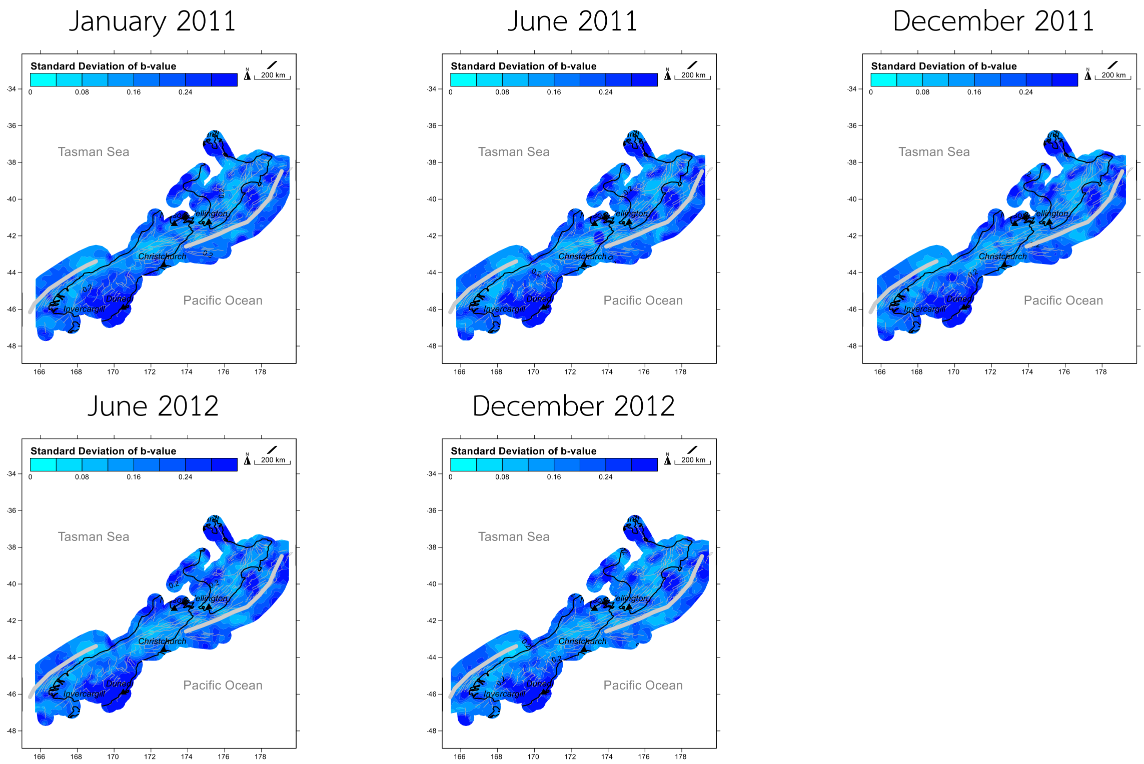


Figure 4.9. Mapping of the standard deviation of present day (1964-2012).

CHAPTER V

DISCUSSION AND CONCLUSION

5.1. Earthquake Catalogue

The earthquake catalogue in this study was from International Seismological Center (ISC). The data consisted of 182,986 events, since 1 January 1964 to 31 December 2016. The magnitude was between 0.1 – 8.1 with depth 0 – 827 km.

5.2. Earthquake Catalogue Improvement

According to incompleteness of catalogue, we needed to improve data before using them to analyze b values. The improvement had these following methods.

5.2.1. Magnitude conversion

In order to several magnitude scales, such as M_W, M_L, M_S and m_b, it was very important to convert the catalogues to the same form which used these relative Equations.

- Moment magnitude (M_w) and body-wave magnitude (m_b)

$$M_W = 0.0077m_b^2 + 0.4669m_b + 2.5893$$

- Moment magnitude (M_w) and surface-wave magnitude (M_S)

$$M_W = -0.0646M_S^2 + 2.0318\ M_S – 4.1368$$

- Body-wave magnitude (m_b) and local magnitude (M_L)

$$m_b = 0.1089\ M_L^2 – 0.0911M_L + 2.5427$$

5.2.2. Earthquake de-clustering

After removing foreshock and aftershock, the catalogue remained the main shocks 28,733 events in 1964 – 2016. The magnitude was between 0 – 8.1 M_W , depth 0 – 722.5 km.

5.2.3. Man-made seismicity

After eliminating man-made seismicity, the data remained 19,012 events in 1978 – 2012. The magnitude was between 3.3 – 8.1 M_W with depth 0 – 722.5 km.

5.2.4. Magnitude of completeness

The magnitude of completeness (Mc) equals 4. The catalogues were left 10,651 events in 1978 – 2012. The magnitude was between 4 – 8.1 $M_{W.}$

After we improve the catalogue through all of the following methods, the changing of data can be detailed in Table 5.1.

Table 5.1. The earthquake catalogues after improvement

Earthquake catalogue improvement	No. of events	Time (year)	Magnitude (M_W)	Depth (km)
1.) Magnitude conversion	182,986	1964-2016	0.1-9.0	0 - 827
2.) Earthquake de-clustering	28,733	1964-2016	0.1-8.1	0 – 722.5
3.) Man-made seismicity	19,012	1978-2012	3.3-8.1	
4.) Magnitude of completeness	10,651	1978-2012	4.0-8.1	

5.3. Case Study and Condition for Retrospective Test

This study selected 6 events of case study (Table 4.1). When we did retrospective test, we found that the most appropriate number of event for analyzing earthquake behavior is 50 events for 0.25 x 0.25 grid nodes, set the minimum events was 5, covering New Zealand.

5.4. Evaluation of Prospective Area

According to the retrospective test, the number of 50 events was the most appropriate parameter of the study area. The epicenter matched with low b-value area (blue) in most of the cases study. However, in some cases, they were between the low and high b-value area (blue and green area) in Figure 5.1.

As reported by Pailoplee (2013), he found that even though we selected the most suitable parameter of the study area, the epicenter can occur between low and high b-value area such as in Northern Thailand, Sumatra-Andaman subduction zone and Philippines island (Figure5.2).

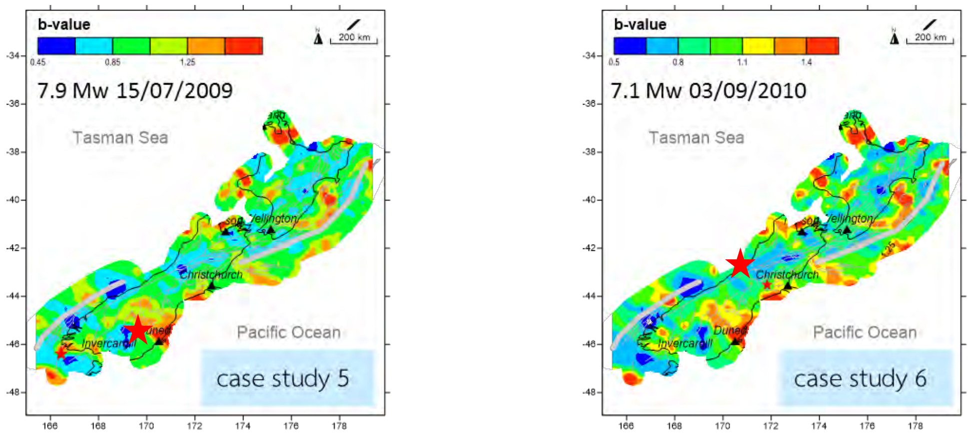


Figure 5.1. The epicenter (red star) is between low and high value (blue and green area).

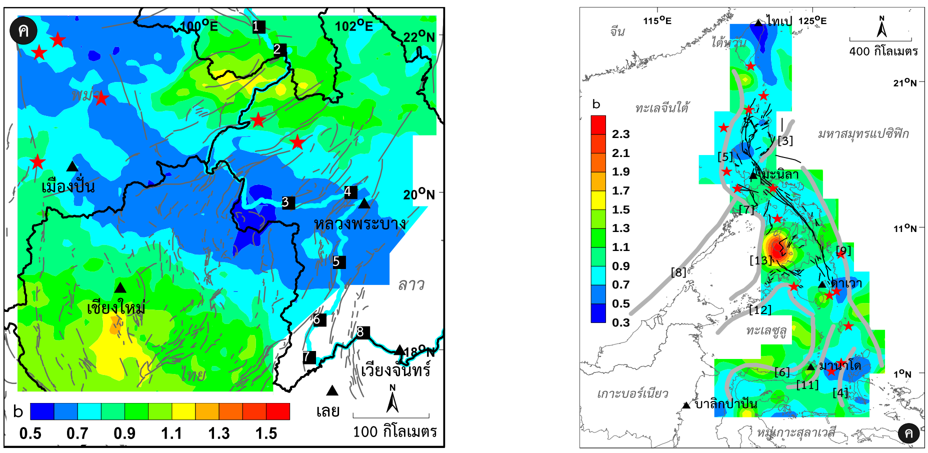


Figure 5.2. The spatial distribution of b value of Northern Thailand in 1984-2005 (Pailoplee et al, 2013a) (left) and Philippines island (Pailoplee and Boonchaluay, 2016) (right)

According to the result, we found 11 anomalous of low b-value areas (Figure 4.7). There are five areas that generated the large earthquake in the past. The study revealed the b value of these zones were low comparison with surrounding areas when the earthquake occurred. After the energy was released as a seismic wave, the decrease in stress accumulation occurred. At that point, the b value had been increasing unless the areas gained the stress again. The b values have been gradually falling until the zones became the anomalous low b value which means the stress have been enhancing again. Hence, these areas may potentially cause large earthquake again.

The rest six zones have never been hit by the large earthquake before. However, the recent result showed that the b values of these areas have been falling. Thus, these zones can generate the large earthquake up to 7 M_W in the future. Another possibility is in the event of they have a frequency in releasing small magnitude. The zones may not occur the large earthquake.

5.5 Comparison of Result and Research

According to the project of Kaewpukum (2017), she examined the seismicity rate change of New Zealand and found that there are 6 anomalous of Z value areas. By comparison of result and this study, found 2 areas that showed anomalous low b value and high Z value which are located in Christchurch (no. 6), New Plymouth and South of Hamilton (no. 8) (Figure 5.2b). These areas may have more potential to generate large earthquake than the others.

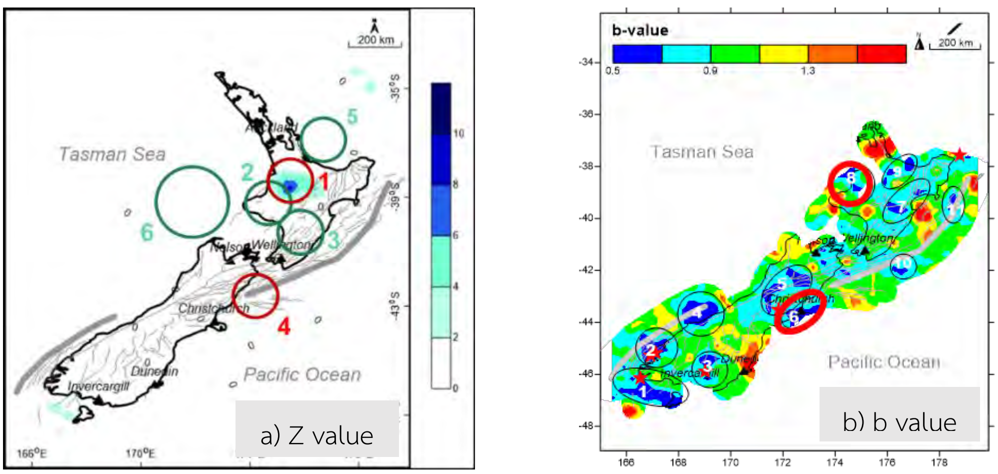


Figure 5.3. Comparison of prospective areas between a) Z-value and b) b-value (1964-2012).

By comparison of result and the research of Wanichthanom (2017), she conducted a study to investigate region-length-time algorithm of New Zealand. The result revealed five prospective areas. There are four areas showed the match of anomaly low Z value and low b value which are Christchurch (no. 6), New Plymouth and South of Hamilton (no. 8), Rotorua and Taupo (no. 9) and eastern coast of Wellington (no. 10) (Figure 5.3c). In the other hand, these zones may have more tendencies to occur the severe earthquake up to 7.0 M_w.

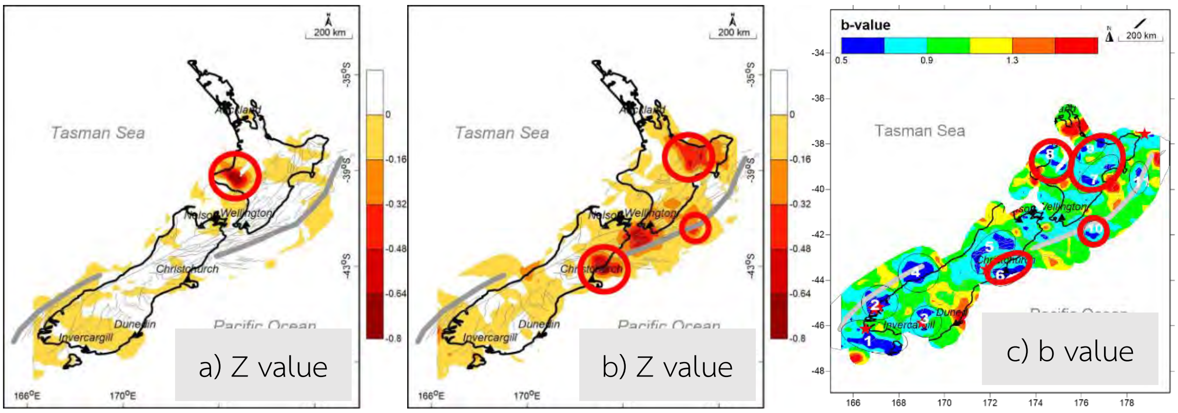
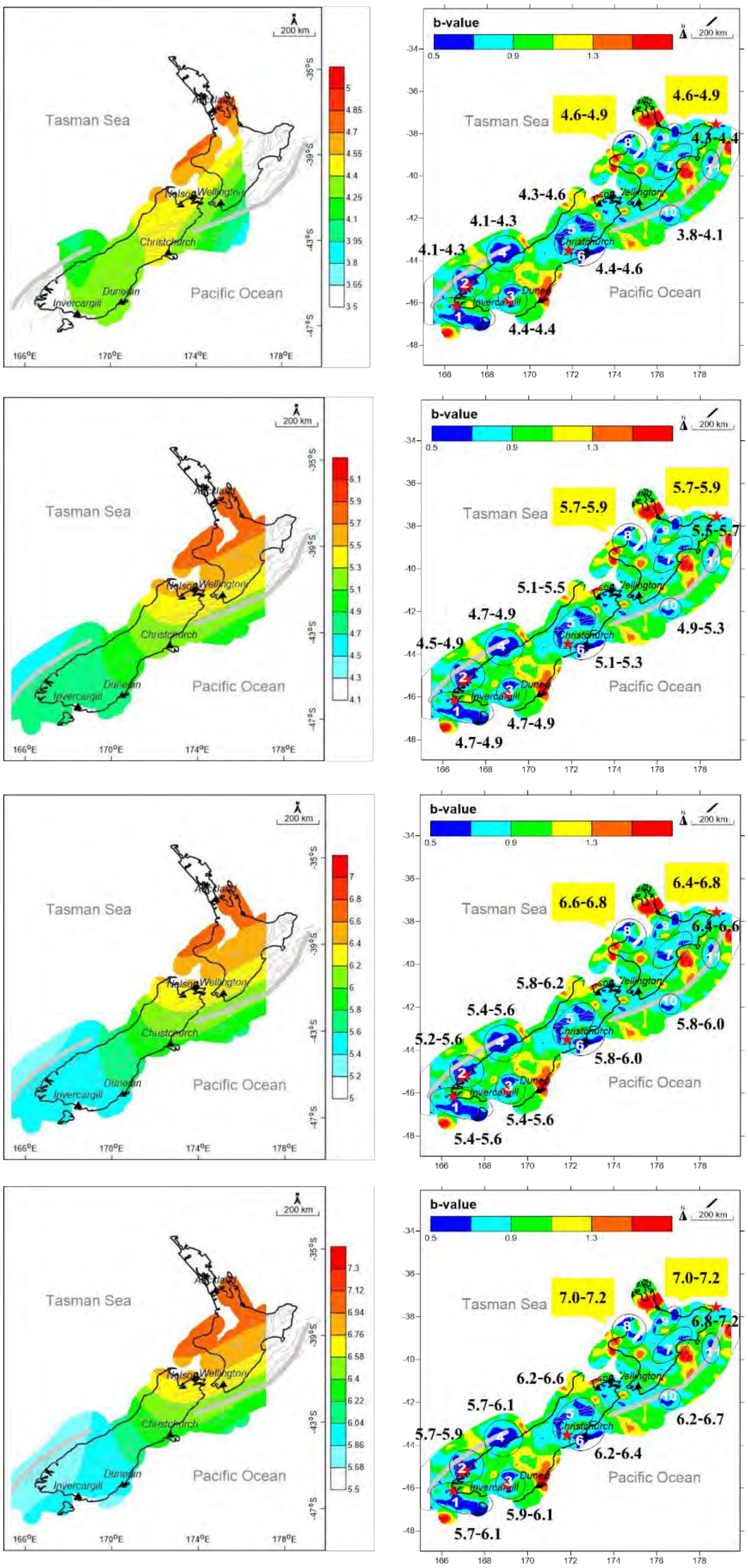


Figure 5.4. Comparison of prospective areas between a) Z value (first condition), b) Z value (second condition) and c) b value (1964-2012)

As reported by the study of Pichetsophon (2017), he examined the maximum magnitude within the coming 5, 10, 30 and 50 years of New Zealand. The correlation between two maps revealed the prospective areas that could hit by the most maximum magnitude is two areas of the Northern Island viz New Plymouth, South of Hamilton, Rotorua and Taupo. The longer they harvest stress, the stronger seismic energy can release.



The maximum magnitude within the coming 5 years (left) and anomalous areas of b value

The maximum magnitude within the coming 10 years (left) and anomalous areas of b value

The maximum magnitude within the coming 30 years (left) and anomalous areas of b value

The maximum magnitude within the coming 50 years (left) and anomalous areas of b value

Figure 5.5. Correlation between the maximum magnitude and the anomalous low b-value (right) of New Zealand (1964-2012).

REFERENCES

Farrell, J., Husen, S., and Smith, R.B. (2008) "Earthquake swarm and b-value characterization of the Yellowstone volcano-tectonic system" Journal of Volcanology and Geothermal Research 188 (2009) 260–276

Gardner, J. K. and Knopoff, L. (1974) "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?" Bulletin Seismol. Soc. Am. 64(1), 363–367.

Gutenberg, B., and Richter C. (1944) "Frequency of earthquakes in California" Bull. Seismol. Soc. Am., 34, 185-188.

Habermann, R. E. (1987) "Man-made changes of Seismicity rates," Bulletin Seismol. Soc. Am. 77, 141–159.

Nuannin, P., Kulh´anek, O. and Persson, L. (2005) "Spatial and temporal b-value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004," Geophys. Res. Lett. 32, L11307.

Nuannin, P. (2006) "The potential of b-value variations as earthquake precursors for small and large events" Acta Universitatis Upsaliensis. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 183. 46 pp. Uppsala.

Okal E.A., and Romanowicz B.A. (1994) "On the variation of b-values with earthquake size" Physics of the Earth and Planetary Interiors 87 (1994) 55—76

Ota K. (2005) "Seminar on b-value" Dept. of Geophysics, Charles University, Prague

Pailoplee, S. (2013) "Mapping asperities along the sagaing fault zone, myanmar using b–value anomalies" Journal of Earthquake and Tsunami Vol. 7, No. 5 (2013) 1371001 (12 pages).

Pailoplee, S., Surakiatchai, P., and Charusiri P. (2013) "b-value anomalies along the northern segment of the sumatra–andaman subduction zone: implications for upcoming earthquakes" Journal of Earthquake and Tsunami Vol. 7, No. 4 (2013) 1350030 (8 pages).

Pailoplee, S., Channarong, P., and Chutakositkanon, V. (2013) “Earthquake activities in the Thailand-Laos-Myanmar border region: a statistical approach” Terr. Atmos. Ocean. Sci., Vol. 24, No. 4, Part II, 721-730, August 2013.

Pailoplee, S., (2016) “Mapping of b-Value Anomalies Along the Strike-Slip Fault System on the Thailand–Myanmar Border: Implications for Upcoming Earthquakes” Journal of Earthquake and Tsunami Vol. 10, No. 3 (2016) 1671001 (13 pages).

Pailoplee, S., and Boonchaluay N. (2016) “Earthquake activities in the Philippines Islands and the adjacent areas” Geosciences Journal DOI 10.1007/s12303-016-0017-x.

Rierola M. (2005) “Temporal and spatial transients in b-values beneath volcanoes” Diploma thesis, ETH Zurich, Institute of Geophysics (77 pages).

Sammonds, P.R., P.G. Meredith, and I.G. Main (1992) “Role of pore fluid in the generation of seismic precursors to shear fracture” Nature, 359, 228-230.

Scholz, C.H. (1968) “The frequency-magnitude relation of micro-fracturing in rock and its relation to earthquakes” Bull. Seismol. Soc. Am. 58, 399-415.

Scholz, C. H. (2015) “On the stress dependence of the earthquake b value” Geophys. Res. Lett., 42, doi:10.1002/ 2014GL062863.

Schorlemmer, D., Neri. G., Wiemer, S., and Mostaaccio, A. (2003) “Stability and significance test for b-value anomalies: example from the Tyrrhenian Sea. Geophys. Res. Lett. 30 (16), 1835.

Utsu, T., 1965. A method for determining the value of b in the formula logN=a-bM showing the magnitude-frequency relation for earthquakes. Geophys. Bull. Hokkaido Univ., 13: 99-103 Wiemer, S. (2001) “A software package to analyze seismicity: ZMAP,” Seismol. Res. 72, 373–382.

Woessner, J. and S. Wiemer 2005: Assessing the Quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty. Bull. Seismol. Soc. Am., 95, 684-698, doi: 10.1785/0120040007.