Variations in Apparent Stress and b Value Preceding the 2010 M_w 8.8 Bio-Bío, Chile Earthquake

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Abstract—We calculated apparent stresses for 70 earthquakes ($M_w \geq 5.0$) occurring in the aftershock region of the 2010 M_w 8.8 Bio-Bío earthquake from January 1990 to September 2019. We identified that the average apparent stress was approximately 0.487 MPa between January 1990 and December 2005 and approximately 1.063 MPa within the period from January 2006 to January 2010. The latter one is 2.2-fold greater than the former, representing a significant difference as determined by a z test, with a 99% confidence level. Moreover, we analyzed the temporal evolution of the apparent stress and found that apparent stress rapidly increased from 0.43 to 1.2 MPa during the pre-event period from March 2006 to the occurrence of the Bio-Bío M_w 8.8 mainshock, and this increased apparent stress was found to be significant at the 98% confidence level. Furthermore, we calculated the spatial distribution of the apparent stress in the study region and observed two higher-apparent-stress regions, within one of which the epicenter of the M_w 8.8 event was located. On the basis of the inverse correlation between b value and stress, the temporal evolution and spatial distribution of b values were calculated and compared with those of the apparent stress. The comparison showed that the b values decreased approximately 4 years before the occurrence of the mainshock, while the apparent stress increased substantially; for the region of lower b , the apparent stress is higher, and vice versa. Therefore, the inverse correlation between b value and stress is supported by the results obtained in the present study and can be probably considered as one of the precursors to great earthquakes.

Keywords: Bio-bío earthquake, apparent stress, b value, variation.

1. Introduction

On February 27, 2010, a strong earthquake struck central Chile. The epicenter reported by the United States Geological Survey (USGS) was located at 36.122° S and 72.898° W, which is offshore to the west of Bio-Bío, Chile. The focal depth was 22.9 km

with an origin time of 06:34:11 UTC, and the moment magnitude of this event was 8.8.

On the basis of Global Centroid Moment Tensor (GCMT) inversion, the fault mechanism of this earthquake was interpreted as a thrust fault on a gently sloping plane along the Peru–Chile Trench (Fig. 1a), where the Nazca plate subducts eastward and downward beneath the South America plate at a rate of 7–9 cm/year (DeMets et al. 1990).

In the rupture zone of the Bio-Bío M_w 8.8 earthquake, strong earthquakes of $M_s \geq 7.0$ have frequently occurred since 1900 (Fig. 2a). The 2010 Bio-Bío M_w 8.8 earthquake occurred in the small region where the January 30, 1914, M_s 8.2 earthquake, December 1, 1928, M_s 8.3 earthquake, and January 25, 1939, M_s 8.3 earthquake, i.e., three large earthquakes, had occurred (Fig. 2b).

Generally, it is believed that the tectonic stress along faults in the crust varies over time. During the loading cycle for great earthquakes, this stress may increase, and the stress may rapidly decrease after a strong rupture. It is difficult to directly detect the stress at the focal source within the focal depth range of a few kilometers to tens of kilometers; therefore, it is very difficult to provide direct evidence for an increased stress at the focal source prior to a strong earthquake. The properties of seismic wave signals are affected by both tectonic stress and source characteristics or source models; however, highly stressed crustal volumes are generally expected to act as sources of pulses enriched in high-frequency energy (Madariaga 1976; Das and Aki 1977; Aki 1979, 1984). Changes in the frequency content of micro-earthquakes prior to larger events have been reported by many researchers (Fedotov et al. 1972;

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Figure 1

a Spatial distribution of epicenters of $M \geq 4.0$ aftershocks that occurred from February 27, 2010, to May 31, 2010, and the GCMT solution for the February 27, 2010, Bio-Bío $M_w 8.8$ earthquake (red star). **b** Epicenters of earthquakes with magnitudes of $M_w \geq 5.0$ occurring from January 1990 to January 2010, as published by the USGS (<https://earthquake.usgs.gov/earthquakes/search/>). The beach ball shows the GCMT solution (NP1: 178°, 77°, 86°; NP2: 17°, 14°, 108°) determined from the Global Centroid Moment Tensor Project (<https://www.globalcmt.org/>). The region marked by the black solid line is the study region in this paper and encompasses the aftershock zone of the Bio-Bío $M_w 8.8$ event. The red thick dotted line indicates the plate boundary

Figure 2

Epicenters of $M_s \geq 7.0$ and $M_s \geq 8.0$ earthquakes from 1900 to 2010. The red star shows the Bio-Bío $M_w 8.8$ event. These earthquake data were obtained from the China Earthquake Network Center (CENC). The red thick dotted line marks the plate boundary. **a** $M_s \geq 7.0$ and **b** $M_s \geq 8.0$

Tsujiura 1977; Bakun and McEvilly 1979, 1981; Ishida and Kanamori 1980).

The apparent stress is a product of the shear modulus and the ratio of seismic energy to the seismic moment (Wyss 1970). Some researchers have applied the apparent stress to study stress changes during the period prior to an earthquake. Average apparent stresses were greater in the coastal zone, but lower in near-trench zones (Zobin 1996). It has been found that small earthquakes with high apparent stress occur in the region in which the mainshock will occur and that the apparent stress significantly increases before a large earthquake (Frank and Carl 1984; Li et al. 2012). Earthquakes with higher apparent stresses occur within an asperity (Zuñiga et al. 1987). Moreover, a recent study demonstrated an increase in the apparent stress before the mainshock followed by decreasing values (Picozzi et al. 2019). However, no change in the apparent stress was observed between foreshocks and aftershocks during the April 6, 2009, M_W 6.1 L'Aquila mainshock; similarly, no increase of the apparent stress was identified before the mainshock (Calderoni et al. 2019).

Mogi (1962) and Scholz (1968a) reported that there was an inverse correlation between the b value and stress through rock fracture experiments. A decrease in the b value in the Gutenberg–Richter relation, $\log N = a - bM$, is interpreted to reflect a stress increase before an impending seismic mainshock (Scholz 1968b; Wyss 1973; Main et al. 1989; Urbancic et al. 1992; Hainzl et al. 1999). A decrease in the b value over a period of months or years has been reported to precede large mainshocks in various parts of the world. For example, Nuannin et al. (2005) reported two significant drops in b values that coincided with the occurrence of two large shocks ($M_S \geq 7.0$) in 2002 and with the M_W 9.0 event in 2004. Decreases in b value or low b values close to the epicenters of certain great earthquakes have been observed in other studies (Imoto 1991; Chan et al. 2012; Enescu and Ito 2001; Nanjo et al. 2012).

There exists no previous research related to regional stress changes during the years before the 2010 Bio-Bío M_W 8.8 earthquake. In this study, we will therefore focus on regional stress changes before this earthquake through apparent stress and b value to

expose how tectonic stress changed during the pre-event period in and around the source region.

2. Study Region and Data Used

The 2010 M_W 8.8 event occurred in the South American arc tectonic belt, which marks the plate boundary between the subducting Nazca plate and the South America plate and where the oceanic crust and lithosphere of the Nazca plate begin their descent into the mantle beneath South America. The convergence associated with this subduction process is responsible for earthquakes along the western edge of the South America plate. This region is part of the east Pacific seismic belt, with a high frequency of strong earthquakes. The region marked by the black lines in Fig. 1 is taken as the study region in this work, which is slightly larger than the rupture zone (aftershock area). The research region is limited to a latitude range of 32° S–39° S.

The apparent stress is defined as follows (Wyss 1970):

$$\sigma_a = \mu \frac{E_s}{M_0} \quad (1)$$

where μ is the shear modulus (for the crustal media, μ can be considered as 3×10^4 MPa), and E_s and M_0 are the radiated seismic energy and seismic moment, respectively. The data used in this study were obtained from the source parameter catalogue published online by Harvard University (www.globalcmt.org/CMTsearch.html). Certain source parameters for earthquakes that occurred between January 1990 and January 2010 ($M_W \geq 5.0$, the maximum $M_W = 6.6$) in the study region are listed in Table 1, for a total of 70 earthquakes. Using the seismic moment and magnitude M_S given in Table 1, E_s is obtained from Formula (2). Then, by applying Formula (1), the apparent stresses for the earthquakes in Table 1 are obtained (Gutenberg and Richter 1956).

$$\text{Log} E_s = 1.5 M_S + 11.8 \quad (2)$$

For each earthquake in Table 1, moment magnitude M_W was given in the catalogue; however, the seismic surface wave magnitude M_S values were

Table 1

Source parameters and apparent stress values for earthquakes occurring in the study region prior to the Bio-Bio M_W 8.8 event

No.	Year-month-date	Latitude (°S)	Longitude (°W)	M_W	M_S	Depth (km)	Moment ($\times 10^{25}$ erg)	σ_{app} (MPa)
1	1990-04-02	33.04	72.63	5.6	5.5	15.0	0.3520	0.9563
2	1990-04-21	37.28	73.79	5.8	5.7	19.9	0.6580	1.0207
3	1990-04-22	38.07	73.60	5.6	5.6	31.0	0.3530	1.3469
4	1990-05-14	35.89	71.34	6.1	5.9 ^a	92.0	1.8800	0.7461
5	1990-10-11	34.17	72.07	5.4	4.9	15.0	0.1630	0.2600
6	1992-04-10	33.68	71.70	5.1	4.7 ^a	32.0	0.0562	0.4146
7	1992-05-03	32.36	71.66	5.5	5.2 ^a	61.0	0.2180	0.5505
8	1992-05-18	33.61	72.03	6.1	5.8	15.0	1.7400	0.5452
9	1992-05-22	33.84	72.42	5.5	5.4	34.3	0.2660	0.8959
10	1993-07-16	33.32	72.56	5.6	5.3	19.2	0.3470	0.4862
11	1993-12-04	33.57	72.22	5.6	4.9	28.8	0.3210	0.1320
12	1994-04-16	32.23	71.84	5.6	5.0	31.3	0.3050	0.1963
13	1994-06-16	32.99	71.96	5.1	4.7 ^a	36.0	0.0484	0.4814
14	1994-09-17	32.48	72.01	5.7	5.3	18.8	0.3910	0.4315
15	1994-09-22	32.07	71.90	5.4	5.1	27.0	0.1810	0.4671
16	1994-10-11	32.22	71.91	5.7	5.3	57.8	0.4690	0.3597
17	1995-03-23	36.33	72.81	5.5	5.5	15.0	0.2050	1.6420
18	1995-07-01	34.14	72.84	5.2	4.4	29.8	0.0763	0.0988
19	1995-09-17	35.61	74.47	5.6	4.8	15.0	0.2740	0.1095
20	1995-11-21	33.33	72.30	5.7	5.3	16.2	0.4450	0.3791
21	1996-02-22	33.53	72.00	5.9	5.5	50.0	0.7860	0.4283
22	1997-06-09	32.08	71.83	5.1	4.7 ^a	67.3	0.0629	0.3705
23	1998-06-06	36.56	73.20	5.2	4.6	15.0	0.0861	0.1746
24	1998-07-29	32.30	71.67	6.4	6.3 ^a	58.0	5.2600	0.9117
25	1998-10-10	33.87	72.48	5.6	5.2	19.8	0.3470	0.3442
26	1999-11-03	37.70	73.93	5.3	4.8	15.0	0.1270	0.2362
27	1999-11-03	37.70	73.64	5.2	4.4	33.0	0.0820	0.0919
28	2000-03-26	32.50	72.16	5.2	4.7	48.9	0.0686	0.3096
29	2001-01-07	33.52	72.33	5.9	5.7	21.0	0.9050	0.7421
30	2001-03-15	32.61	72.04	5.9	5.6	42.0	0.8400	0.5660
31	2001-05-06	32.95	70.92	5.2	4.8 ^a	50.0	0.0686	0.5117
32	2001-07-24	33.22	72.17	5.2	4.7	51.6	0.0799	0.2658
33	2001-11-03	36.19	72.02	5.1	4.7 ^a	99.9	0.0549	0.4244
34	2002-05-24	32.17	71.52	5.5	5.2 ^a	57.0	0.2420	0.4959
35	2002-09-30	35.17	71.07	5.2	4.8 ^a	113.9	0.0942	0.3726
36	2003-02-28	35.41	73.56	5.3	5.1	15.0	0.1310	0.6454
37	2003-04-14	35.38	72.90	5.2	4.8 ^a	31.1	0.0911	0.3853
38	2003-06-02	33.08	72.40	5.5	5.1	28.0	0.2300	0.3676
39	2003-09-28	35.54	71.11	5.0	4.6 ^a	105.2	0.0468	0.3305
40	2004-05-03	37.95	73.75	6.6	6.5	24.0	10.4000	1.0235
41	2004-09-07	34.10	72.49	5.2	4.8 ^a	14.1	0.0822	0.4270
42	2004-09-07	34.14	72.52	5.7	5.3	14.2	0.4040	0.4176
43	2004-09-08	34.13	72.40	5.1	4.5	15.4	0.0502	0.2120
44	2004-09-10	38.06	73.24	5.2	4.9	12.0	0.0931	0.4552
45	2004-09-27	32.72	72.02	5.5	5.1	33.3	0.2250	0.3758
46	2005-03-13	32.72	72.02	5.2	4.8	35.7	0.0834	0.3597
47	2005-03-29	33.76	72.38	5.3	5.0 ^a	19.7	0.1150	0.4598
48	2005-04-13	33.27	73.24	5.4	4.7	12.0	0.1440	0.1475
49	2006-01-05	36.43	73.52	5.2	4.8 ^a	20.0	0.0779	0.4506
50	2006-02-10	32.57	71.84	5.2	4.8 ^a	41.6	0.0774	0.4535
51	2006-05-18	32.34	72.14	5.0	4.9	23.5	0.0454	0.9334
52	2006-05-21	37.41	74.14	5.2	4.8 ^a	15.4	0.0936	0.3750
53	2006-07-19	32.63	72.24	5.0	4.9	31.0	0.0453	0.9355
54	2007-01-07	35.52	71.23	5.0	4.6 ^a	121.4	0.0340	0.4549
55	2007-06-28	32.08	71.63	5.6	5.7	80.3	0.3620	1.8553

Table 1 *continued*

No.	Year-month-date	Latitude (°S)	Longitude (°W)	M_W	M_S	Depth (km)	Moment ($\times 10^{25}$ erg)	σ_{app} (MPa)
56	2007-08-08	32.66	71.92	5.3	5.2	24.0	0.1230	0.9710
57	2007-10-20	36.50	73.51	5.2	4.8 ^a	40.7	0.0798	0.4399
58	2007-12-15	32.81	72.02	5.9	5.9	33.3	0.8850	1.5142
59	2007-12-20	32.85	72.01	5.5	5.3	25.0	0.1940	0.8696
60	2008-10-01	35.03	71.04	5.2	4.8 ^a	118.6	0.0736	0.4769
61	2008-11-23	36.38	73.36	5.3	5.3	37.8	0.1070	1.5767
62	2008-12-18	32.63	72.13	6.1	6.2	22.5	1.9500	1.9368
63	2008-12-18	32.62	72.11	5.9	6.0	20.7	0.7580	2.4972
64	2008-12-19	32.66	72.24	5.4	5.1	22.0	0.1530	0.5526
65	2008-12-19	32.56	72.10	5.7	5.7	23.1	0.4860	1.3819
66	2008-12-19	32.68	71.97	5.2	5.1	24.3	0.0853	0.9912
67	2008-12-19	32.60	72.25	5.2	4.9	29.4	0.0722	0.5869
68	2009-09-25	32.26	71.90	5.1	4.7 ^a	41.8	0.0522	0.4464
69	2009-10-28	32.84	72.05	5.0	4.6 ^a	19.0	0.0386	0.4007
70	2009-12-29	36.78	73.39	5.1	5.3	43.4	0.0512	3.2950

^aCalculated from Formula (3)

lacking for 22 earthquakes. Based on the M_W and M_S magnitudes given for other 48 earthquakes, the following relationship was obtained, with a correlation coefficient of 0.84 and a standard deviation of 0.25.

$$M_S = 1.1864M_W - 1.3238 \pm 0.25 \quad (3)$$

A total of 279 earthquakes ($5.0 \leq M_W \leq 6.9$) occurred between February 27, 2010, and September 30, 2010; however, M_S values are lacking for 58 of these earthquakes. For the 221 earthquakes with a given M_S value, we obtained the following relationship, with a correlation coefficient of 0.92 and a standard deviation of 0.0551.

$$M_S = 1.099M_W - 0.57839 \pm 0.0551 \quad (4)$$

The M_S magnitudes marked by a “a” in Table 1 were calculated using Formula (3), and the apparent stress values are listed in Table 1.

3. Results

The events occurring within the period of January 1990 to September 2019 were listed in a chronological order. We used sliding windows of 15 events, shifted by two events per time. We considered the first 15 events as a sample to calculate the first average apparent stress; then, by moving two events, we considered a second sample of 15 events (nos. 3–

17) to calculate the second average apparent stress. The average apparent stress obtained herein is the 15-event mean of the apparent stress. The occurrence time point of the last event in each sample is considered as the time for the average apparent stress value. In this manner, as shown in Fig. 3, we obtained the average apparent stress versus time. The figure shows that $\bar{\sigma}_a$ remained stable before 2006, increased between 2006 and 2009 with an accumulation of an increase of ~ 0.76 MPa (within the rectangle enclosed by dashed lines), and increased rapidly when the Bio-Bío $M_W 8.8$ mainshock was occurring. During the period of several months after the mainshock, the average apparent stress exhibited large-amplitude fluctuations, and then went to a subsequent stationary variation at a low level. In this work, we are interested in the increased apparent stress preceding the Bio-Bío $M_W 8.8$ mainshock. Therefore, in the following section, we will focus on the significance of this increase during the pre-event period.

Figure 4 shows the observed apparent stress as a function of time for each event that occurred prior to the Bio-Bío $M_W 8.8$ mainshock. Between January 1990 and December 2005, 48 events occurred, with an average apparent stress (denoted by $\bar{\sigma}_{al}$) of approximately $0.487 \text{ MPa} \pm 0.316$, which is very close to the globally averaged apparent stress (0.47 MPa) (Choy and Wright 1995). However,

Figure 3

Fifteen-event mean of apparent stress versus time. “↓” denotes the occurrence timepoint of the 2010 Bio-Bío M_w 8.8 mainshock

Figure 4

Apparent stress as a function of time. “↓” denotes the occurrence time of the 2010 Bio-Bío M_w 8.8 mainshock

during the period from January 2006 to December 2009, 22 events occurred, with an average apparent stress (denoted by $\overline{\sigma_{a2}}$) of approximately $1.063 \text{ MPa} \pm 0.778$. The maximum value of σ_a increased from 0.45 MPa in the beginning of 2006 to 3.3 MPa at the end of 2009, at a rate of approximately 0.71 MPa/

year. Here, $\overline{\sigma_{a2}}$ is 2.2-fold greater than $\overline{\sigma_{a1}}$; thus, it is possible that the difference between these two values is significant. The standard deviation z test can be applied to assess the statistical significance of the difference between two known means, M_1 and M_2 ,

Figure 5

The average apparent stress versus time. “↓” denotes the occurrence time of the 2010 Bio-Bío M_w 8.8 mainshock: **a** 15-event mean, shifted by two events per time; **b** 30-event mean, shifted by two events per time

Figure 6

Results of statistical test for the increase in average apparent stress during the period before the 2010 Bio-Bío M_w 8.8 mainshock

with standard deviations of S_1 and S_2 (Zuñiga et al. 1987), where z is defined as follows:

$$z = \frac{M_1 - M_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad (5)$$

Here, n_1 and n_2 are the number of samples for each dataset. For the difference between $\overline{\sigma_{a1}}$ and $\overline{\sigma_{a2}}$, we obtained $z = 3.35$, indicating a significant difference at the 99% confidence level.

Furthermore, we examined the significance of the increase in the average apparent stress prior to the mainshock. Figure 5 shows the average apparent stress versus time during the pre-mainshock period, based on both the 15-event and 30-event mean, shifted by two events per time. The statistical results for these data are shown in Fig. 6, which shows that the increases in both the 15-event and 30-event mean are significant at a 98% confidence level.

Figure 7

a Average apparent stress versus time with the inclusion of random errors. The red curve corresponds to the raw data curve shown in Fig. 5a, the blue curve shows the average value of the experimental curves, and the two dark solid lines indicate the maximum and minimum values. The light cyan area indicates the uncertainty limit. **b** Cumulative frequency distribution of correlation coefficients for the raw data curve and the experimental curves

M_S magnitudes are missing in the catalogue for certain earthquakes. For these events, we calculated the M_S values on the basis of Formula (3) or (4). Some errors may arise in this process, particularly for Formula (3). To evaluate the uncertainty associated to the average apparent stress, an error with an absolute value of no greater than 0.25 [the standard deviation in Formula (3)] was randomly introduced as M_S was calculated, and then we computed the curve of the average apparent stress versus time. For the situation shown in Fig. 5a, this process was repeated 2000 times. A total of 2000 experimental curves were thus obtained, and their average values are plotted by the blue line in Fig. 7a, with the red line corresponding to the raw data curve displayed in Fig. 5a. The two dark solid lines indicate the maximum and minimum values for the 2000 experimental curves. The correlation coefficient for the average curve and the raw data curve is 0.9998. Figure 7b shows the cumulative frequency distribution of correlation coefficients for the raw data curve and each of the 2000 experimental curves. A total of 2000 correlation coefficients were obtained, with a minimum correlation coefficient of ~ 0.9577 , an average of 0.9919, and a maximum of 0.9995. The higher correlation coefficients are

attributed to better agreement between the experimental and raw data curve.

Therefore, the uncertainty arising from errors in M_S because of Formula (3) does not mask the temporal evolution of the average apparent stress.

To investigate the spatial distribution of the apparent stress, we applied a spatial window of $0.8^\circ \times 0.8^\circ$ that moved by 0.4° in both the latitudinal and longitudinal directions. Figure 8 shows the spatial distribution of the apparent stress for earthquakes that occurred in the study region ($5.0 \leq M_w \leq 6.6$), which was plotted by applying a cubic spline interpolation with a $0.1^\circ \times 0.1^\circ$ grid. Figure 8a is for earthquakes that occurred from 1990 to 2005, and Fig. 8b is for earthquakes that occurred from 2006 to January 2010. Three distinct areas of relatively high apparent stress of over 1.0 MPa can be seen in Fig. 8a. One area is observed near the epicenter of the 2010 Bio-Bio $M_w 8.8$ event, and two regions are located in the southern area, between 39° S and 37° S. The region near the epicenter is more distinct and enhanced to the highest apparent stress of about 3.3 MPa and developed within 3 years before the 2010 Bio-Bío $M_w 8.8$ event (Fig. 8b).

Figure 8

Spatial distribution of the apparent stress. The blue star indicates the epicenter of the 2010 Bio-Bío M_w 8.8 mainshock, and the red thick dotted line marks the plate boundary. **a** Earthquakes that occurred from 1990 to 2005. **b** Earthquakes that occurred from 2006 to January 2010. A spatial window of $0.8^\circ \times 0.8^\circ$ was moved by 0.4° in both the latitudinal and longitudinal directions. A cubic spline interpolation was applied with a $0.1^\circ \times 0.1^\circ$ grid

As mentioned above, the apparent stress in the aftershock area exhibited a significant increase 3 years before the occurrence of the 2010 Bio-Bío M_w 8.8 mainshock. Thus, we investigated whether this result can be supported by a variation in the b value. In the following, we investigate the b value as a function of time in the study region and its spatial distribution. The maximum likelihood method was applied to estimate the b value (Aki 1965):

$$b = \frac{\log e}{\bar{M} - M_{\min}} \quad (6)$$

The 95% confidence standard deviation of b is

$$\sigma(b) = 1.96 \frac{b}{\sqrt{N-1}} \quad (7)$$

where $\bar{M}$ and $M_{\min}$ represent the average magnitude and the minimum magnitude of events of the given sample, respectively, and N is the total number. We selected data from the global earthquake catalog published by the USGS (<https://earthquake.usgs.gov/>

[earthquakes/search/](#)). There were 4443 earthquakes ($M \geq 3.6$) in the study region over the period of January 1990 to January 2010. For estimating b values, the completeness of the earthquake catalogue should be considered with respect to the observed Gutenberg–Richter relation via visual inspection. From Fig. 9a, a threshold magnitude of 3.7 was derived. We computed the magnitude of completeness M_C as a function of time according to the maximum curvature technique, using sample sizes of 1500 events and a step size of 100 events. Note that M_C as a function of time shows values of $M_C \leq 3.7$ since the year 1990 (Fig. 9b); the corresponding magnitudes are plotted as a function of time in Fig. 10. The epicenters of these earthquakes are shown in Fig. 11a, located within the aftershock zone. Figure 11b shows the vertical profile along line B–B1 perpendicular to line A–A1 (the trace of the focal fault at ground) and indicates that a great majority of the selected events are associated with plate-interface activity. The b value was calculated as

Figure 9

a Cumulative number of earthquakes versus magnitude. Threshold magnitudes M_c (downward filled triangle) and the overall b value (1.18) are also displayed. **b** Magnitude of completeness M_c as a function of time was computed according to the maximum curvature technique, using sample sizes of 1500 events and a step size of 100 events

a function of time using a time window comprising a constant number of events, n . The window was moved in time by an increment of event counts. We applied a constant number of events in each window

(rather than windows with a constant time width) to ensure that the analysis was not influenced by a change in sample size. To calculate the b value as a function of time, 3705 earthquakes with $M \geq 3.7$

Figure 10
Magnitude versus time for earthquakes ($M \geq 3.7$)

were selected, and a sliding time window containing 500 events and moving by five events was utilized. Figure 12 shows the b value (red line) as a function of time, where the black solid lines indicate the 95 percent confidence limit. The b value began to decrease in April 2004 and reached a value below 1.2 in February 2006. Thereafter, the b value decreased until the occurrence of the 2010 Bio-Bío M_w 8.8 mainshock, accumulating a reduction of ~ 0.3 . The average apparent stress as a function of time shown in Fig. 5a is also plotted as a blue line in Fig. 12. The figure shows that the b value decreased approximately 4 years prior to the main shock. Furthermore, the average apparent stress showed a significant increase. Therefore, this result is consistent with the inverse correlation between the variation of stress and b value change.

We calculated the spatial distribution of the b value for earthquakes that occurred in the study region by applying a spatial window of $150 \text{ km} \times 150 \text{ km}$ moving by 10 km in both the latitudinal and longitudinal directions. To obtain a greater number of windows containing a sufficient number of events for calculating the b values, earthquakes with $M \geq 3.7$

were used. For the b value estimation, the windows included 30 events or more. The spatial distribution of the b values is shown in Fig. 13, where the blue corresponds to low b values and the red indicates high b values. There were two low b areas in the aftershock region, one centered near the epicenter from 2006 to January 2010, and another at the northern end of the aftershock region (Fig. 13b). By comparing Figs. 13b and 8b, we can identify a distinct inverse correlation between the b value and the apparent stress: in the region of low b values, the apparent stress is high, and vice versa. Therefore, the decrease in b value can be explained in terms of the increase in stress.

The difference of the spatial coverage between Fig. 13a and b can be found. The limitation for b value calculation is 30 events or more. It may result in difference of the spatial coverage.

Figure 14 shows the standard deviation σ (obtained by bootstrapping) of the b values, showing that σ is smaller in the areas with a lower b value (Fig. 13); therefore, the areas of lower b values are statistically reliable. Figure 15a shows the differences in b values during the periods of January 1990–

Figure 11

a Epicenters of earthquakes ($M \geq 3.7$) that occurred between January 1990 and January 2010, which were used for the b value calculation. Line A–A1 shows the trace of the focal fault at ground, and line B–B1 is perpendicular to line A–A1. **b** Vertical profile along B–B1. The red star denotes the Bio-Bío $M_{\text{W}}8.8$ event

December 2005 and January 2006–January 2010, in which $\Delta b = b_{2006-2010} - b_{1990-2005}$. We identified two areas with distinct changes in b value, one at the northern end of the aftershock region, and another located northeast of the epicenter of the Bio-Bío $M_{\text{W}}8.8$ mainshock, with its center 180 km away from the epicenter. No marked change in b value is exhibited near the epicenter.

Difference in b value is quantified by applying the Utsu test (Utsu 1992; Schorlemmer et al. 2004). The probability P_b that the b values are not different is determined by (Akaike 1974)

$$P_b = e^{\left(\frac{-\Delta\text{AIC}}{2} - 2\right)} \quad (8)$$

$$\begin{aligned} \Delta\text{AIC} = & -2(N_1 + N_2) \ln(N_1 + N_2) \\ & + 2N_1 \ln\left(N_1 + \frac{N_2 b_1}{b_2}\right) \\ & + 2N_2 \ln\left(N_2 + \frac{N_1 b_2}{b_1}\right) - 2 \end{aligned} \quad (9)$$

where b_1 and b_2 are the b values for two different periods; N_1 and N_2 are corresponding values of N . According to Utsu (1999), application the logarithm leads to $\log P_b \leq -1.3$ for significantly different b values and $\log P_b \leq -1.9$ for highly significant differences in b values. The spatial distribution of probability P_b is displayed in Fig. 15b, where blue lines denote contours of $\log P_b = -1.3$. It is revealed from Fig. 15b that the above two areas with marked changes in b value are significantly different.

Figure 12

b values (red line) as a function of time for the study region, which was obtained by applying a sliding time window of 500 events moved by five events. The light green area indicates the 95% confidence limit obtained from Formula (7). The blue line shows the 15-event mean of apparent stress. The vertical arrow “↓” marks the time of occurrence of the 2010 M_w 8.8 mainshock

Figure 13

Spatial distribution of b value within the study region, for which earthquakes of $M \geq 3.7$ were used. The blue data show low b values, whereas the red data indicate high b values. The red star indicates the epicenter of the 2010 Bio-Bío M_w 8.8 mainshock, and the red thick dotted line marks the plate boundary. **a** Earthquakes that occurred from 1990 to 2005. **b** Earthquakes that occurred from 2006 to January 2010. A spatial window of $150 \text{ km} \times 150 \text{ km}$ was moved by 10 km in both the latitudinal and longitudinal directions

Figure 14

Spatial distribution of standard deviation obtained by bootstrapping with a sample size of 2000. **a** In the period from January 1990 to December 2005; **b** in the period from January 2006 to January 2010

4. Discussion and Conclusions

By analyzing earthquakes that occurred in the Bio-Bío region, we assessed the variations in apparent stress as a function of time before the 2010 Bio-Bío M_w 8.8 mainshock and found a significant increase during the pre-mainshock period. Moreover, we obtained the spatial distribution of the apparent stress and identified two distinct high-apparent-stress areas in the aftershock region, one of which was located near the epicenter of the M_w 8.8 mainshock. Similar results were presented for the 2011 Tohoku, Japan, M_w 9.1 earthquake (Li and Chen 2017). Moreover, we calculated the b value as a function of time and the corresponding spatial distribution for earthquakes that occurred in the study region. The b value began to decrease in April 2004 and began decreasing more rapidly in February 2006. Thereafter, the b value decreased until the occurrence of the 2010 Bio-Bío M_w 8.8 mainshock, while the apparent stress significantly increased. By comparing the spatial distribution of the b values with that of the

apparent stress, we reported a distinct inverse correlation between b value and apparent stress: in regions of low b values, the apparent stress is high, and vice versa. In Mogi (1962) and Scholz's (1968a) experiments, the low b value corresponds to the high stress. If the apparent stress can reflect the tectonic stress, the reverse correlation between the increase of the apparent stress and the decrease of the b value may uniformly reflect the change process of the increase of the tectonic stress.

From the above results, we do not find significant changes in b value in the area near the epicenter. It is possible that an inverse correlation exists between the b value and apparent stress in the area near the epicenter. To evaluate this possibility, we calculated b value as a function of time in the area with latitudes ranging from 37.5° S to 35.5° S using a time window containing 100 events moved by one event. The results of this assessment are shown in Fig. 16, which demonstrates an inverse correlation between the b value and apparent stress in the area near the epicenter since 2006. Therefore, an inverse correlation

Figure 15

Results of the stationarity test comparing the periods January 1990–December 2005 and January 2006 to January 2010: **a** differences in b values between the periods January 1990–December 2005 and January 2006–January 2010. **b** log-probability of b values with nonstationary behavior according to Utsu (1992). Blue lines denote contours of $\log P_b = -1.3$

Figure 16

b values (red line) as a function of time latitudes ranging from 37.5° S to 35.5° S in the study region, obtained by applying a sliding time window of 100 events moved by one event. The light green area indicates the 95% confidence limit. And the blue line shows the 15-event mean of apparent stress. The vertical arrow “↓” marks the time of occurrence of the 2010 $M_w 8.8$ mainshock

between b value and apparent stress existed in both the whole aftershock region and the area close to the epicenter.

From this discussion, it can be concluded that the region surrounding the aftershock area was subjected to a significantly increasing stress over a period of approximately 4 years before the 2010 Bio-Bío M_W 8.8 event. This is supported by the inverse correlation between the b value and the apparent stress, which can be probably considered as one of precursors to great earthquakes.

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