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Characteristics of focal mechanisms in Chile subduction

Wang Xiaoshan, Diao Guiling, Feng Xiangdong and Yang Yaqiong
Earthquake Administration of Hebei Province, Shijiazhuang 050021, *China*

Abstract: We use the Centroid Moment Tensor (CMT) solution of the earthquakes occurred in Chile subduction to analyze the characteristics of focal mechanisms. We define the angle between P, B, and T axes of focal mechanisms and three stress axes of tectonic stress field as the consistency parameter, to research the dynamic changes of focal mechanism pattern in earthquake preparation area before the 2010 Maule, Chile earthquake. The result shows that the consistency parameter decreases before the earthquake, and the area of the lower consistent parameter visually coincides with the distribution of aftershocks. This phenomenon is similar to the Load-Unload Response Ratio (LURR) decreases prior to the occurrence of macro-fracture happened in the acoustic emission experiments involving large rock specimens under tri-axial stress.

Key words: 2010 Maule earthquake; Centroid Moment Tensor (CMT) solutions; consistency parameter; Chile subduction; Load-Unload Response Ratio (LURR)

1 Introduction

Chile is the site of some of the largest earthquakes in the world: On average, a magnitude 8 earthquake occurs there every 10 years or so. An earthquake of *M*w8.8 occurred on the Chilean subduction near the cities of Concepcion, Constitucion and Valparaiso on Saturday, 27 February 2010. This area lies immediately to the north of the rupture zone associated with the great 1960 earthquake, of magnitude 9.5[1,2] and part of the region was affected by the 1939 Chillán earthquake (magnitude 7.9). Recent studies have demonstrated that the 1939 earthquake was not a typical subduction earthquake, but was a slab-pull event due to the release of tensional stresses within the down-going slab[3,4]. The 2010 Maule earthquake filled an obvious seismic gap (Fig. 1), that of south-central Chile between 35° and 37°S, had been considered the oldest seismic gap in Chile[5], with its last large earthquake dating back to 1835[6]. Many seismological and GPS studies have taken a closer look into the area. They discovered that the plate interface was completely locked (coupled), so that stress was building up at the fastest possible speed. Interpretation of the geodetic data showed that coupling along the Chilean subduction zone changes widely from south to north but is the largest in the most ancient gaps[7].

Focal mechanisms of earthquakes are the basic data for studying the regional tectonic stress field. Therefore, the temporal evolution of the stress field in the source region derived from the focal mechanisms of earthquakes in this region is important for understanding and forecasting the process of earthquake preparation. Under the frame of elasticity, the precise determination of stress magnitude in seismogenic area is very difficult[8], but the stress direction can be obtained by using earthquake focal mechanism[9-12]. So by treating the convergence of stress field direction from focal mechanism of foreshock and that from main shock before a big earthquake as a parameter, we may be able

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Corresponding author: Diao Guiling. E-mail: dgl@eq-he.ac.cn.
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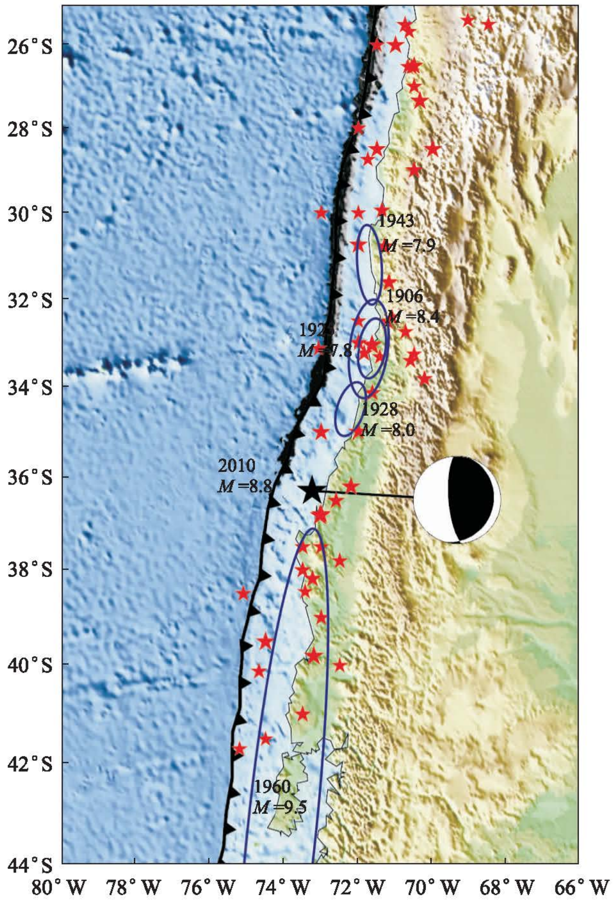


Figure 1 Shaded relief map of the Andean subduction zone in South-Central Chile. Earthquake segmentation along the margin is indicated by ellipses that encloses the approximate rupture areas of historic earthquakes[4-6]

to obtain some information about the earthquake preparation process before a large earthquake. In the late 1970s, Chen proposed the method of treating the focal mechanisms consistency as a new parameter to describe the earthquake preparation process[13]. Diao et al[14] developed the method of calculating the sum of the angles between the P, T and B axis of focal mechanisms and the pressure, dilatational and intermediate principal stress axis of tectonics stress and treated the average value as the consistency parameter. They found that the consistency parameter decreased before all the $Mw \geqslant 7.5$ earthquakes in the Kuril Islands arc[14,15] and in Peru[16]. Wan and Sheng[17-19] used the FMOA (Focal Mechanism Orientation Angle) algorithm[18, 19] to the small earthquake focal mechanism catalog given by Hauksson for studying the phenomena that small earthquakes focal mechanisms trend to that of mainshocks for Landers earthquake and Hector Mine earthquake in southern California[20], and found that the above mentioned phenomenon is significant in both earthquakes. In this study, the optimal double-couple solution of CMT (Centroid Moment Tensor) solutions is adopted and the consistency parameter method is used to probe the pattern of focal mechanisms observed before the 2010 Maule earthquakes.

2 Data and Method

The earthquakes (star in Fig. 1) portrayed on the main map are taken from the earthquake catalog ($Ms \geqslant 7.0$) of Department of Geophysics, University of Chile (http://ssn.dgf.uchile.cl/seismo.html). The CMT solutions used in this paper are downloaded from Global Centroid Moment Tensor database (http://www.globalcmt.org/CMTsearch.html), whose centroid depth must be less than 70 km. From Apr. 20, 1990 to Feb. 27, 2010, earthquakes occurred basically one after another and no long a seismic period was observed (Fig. 2), the CMT solutions for 223 earthquakes are available. Xue et al[21] evaluated the completeness of the earthquake catalogue in South American Plate and

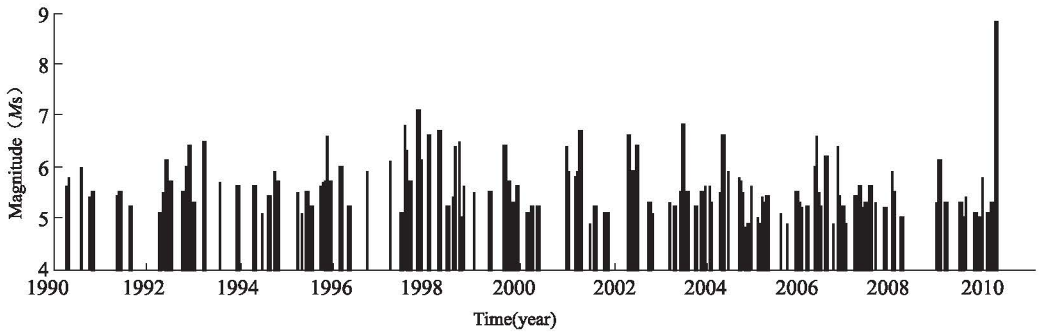


Figure 2 M-t distribution of CMT catalogue in study area

its approach shows that the correlation coefficient R is 0.997 and b-value is 1.05, and there is no "roll off" at the lower magnitude end. So the catalogue of $Ms \geqslant 5.0$ earthquakes is complete in the area.

The stress field is expressed by 3 principal stress axes σ_1, σ_2, σ_3, that are perpendicular to one another; and the orientations of focal mechanism are shown by 3 stress axes of P, N, T that are perpendicular to one another (Fig. 3). Then, the consistency parameter[14] for the focal mechanism relative to the tectonic stress field is

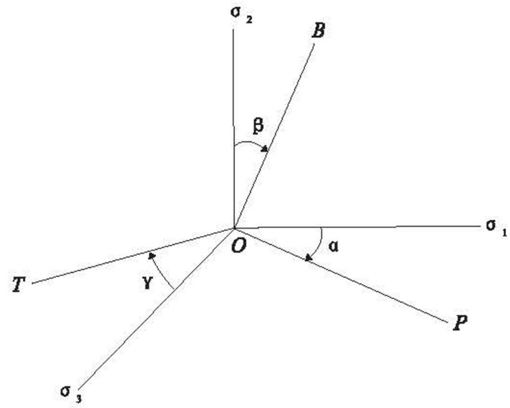


Figure 3 Included angles for 3 principal axes N, P and T of tectonic stress field and principal stress axes of focal mechanism

$$\alpha = \alpha + \beta + \gamma \quad (1)$$

Where $\alpha = \angle\sigma_1 OP$, $\beta = \angle\sigma_2 ON$, $\gamma = \angle\sigma_3 OT$. The maximum value for the consistency parameter is 270° and the minimum value is 0°. A low value indicates that the P, N and T axis lie very close to the principal stress axis.

3 Calculation and Results

Figure 4 shows the normalized frequency distribution per 10° for different parameters of 223 focal mechanism solutions. In the statistics of nodal-plane parameters, the fault plane and auxiliary plane are not separated from each other, but are calculated together. The strike of the fault plane is NS that is consistent with the orientation of the subduction zone between the Nazca plate and South America plate. The absolute majority of rake angles are located in the vicinity of 90° with an underthrust pattern. The dip angles can be divided into

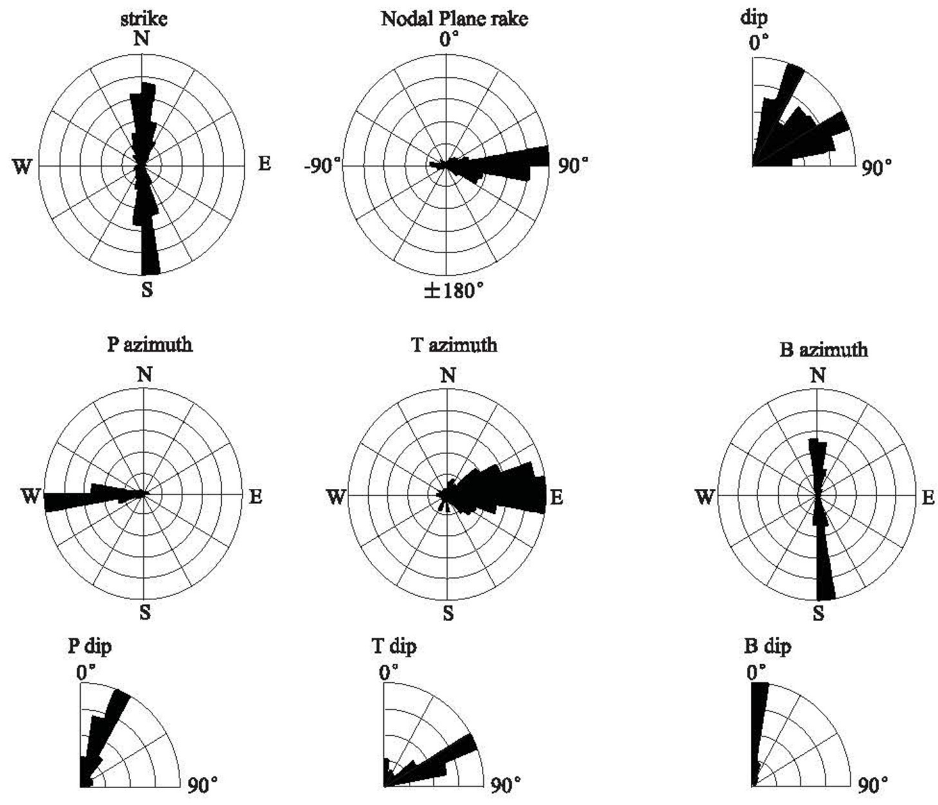


Figure 4 Normalized frequency distribution per 10° for different parameter of CMT optimal double-couple solutions

two groups, one is about 60° and the other is about 30°. 30° or so is just the underthrust angle of Nazca plate in this area and 60° or so is the dip angle of auxiliary plane. The P-axis azimuths basically have a western orientation that is the same as the movement direction of Nazca plate here, the P-axis dip angles are very low with a majority of 20° – 30° that is corresponding to the low-dipping subduction; the T-axis azimuths are a little bit scattered, but they are mainly concentrated on the eastern orientation, the T-axis dip angles are higher with a majority of 60° – 80°; the N-axis azimuths are also very concentrated with the direction that is the same as the strike of fault plane and most N-axis dip angles are near the horizontal line. Although the seismicity in the Peru-Chile Trench is intensive, the focal-mechanism solutions of the earthquakes are very consistent. The dominant orientation of focal mechanism obtained from the data in the period as long as 20 years corresponds to the movement pattern of the local plate, which enables us to propose the idea to make earthquake prediction with the consistence of focal mechanism and stress field.

The reference frame of stress filed in central Chile subduction is determined by the FMSI (Focal Mechanism Stress Invevsion) method with 222 focal mechanism solutions before the 2010 Maule earthquake[22], the azimuths and dips of principal stress axes, σ_1, σ_2, σ_3, are 265° and 25°, 355° and 0°, 86° and 65°, respectively. Then the consistency parameter α of each focal mechanism and tectonic stress field is calculated in the 3-D space[14].

The consistency parameter α calculated for each focal mechanism is shown in figure 5. The consistency parameter α for the ordinate is shown in degree and the abscissa indicates the time sequence of earthquake occurrences. The distribution of α appears to be largely bimodal. There is a set of values that cluster around 30° – 40°, and another set that clusters around about 150°. We use the consistency parameter of 60° as the threshold value (dashed line in Fig. 5), which means the focal mechanisms with α less than 60° trend to the principal stress axes of tectonic stress field in central Chile subduction. The consistency parameter less than 60° accounts for 57.6% in whole. But the numbers of focal mechanisms with α less than 60° has increased since 2006, before the Maule earthquake the focal mechanisms with α less than 60° account for 75%, which indicates the focal mechanisms is consistent with the stress field in the central Chile subduction and the Nazca plate speedily underthrust to the South American plate. These earthquakes with lower consistency parameter occurred on the outside of the oldest seismic gap (Fig. 6(b)), where the rock is relative broken and difficult to cumulate high stress. From Feb. 29 to Nov. 23 in 2008, there is no earthquake with magnitude more than 4.7 in central Chile subduction, which indicates the stress state is accumulated and the seismic risk is gradually increased. After this period the consistency parameters is discrete. The same phenomenon happened in the acoustic emission experiments involving large rock specimens under tri-axial stress. Prior to the final failure of the specimens the LURR (Load-Unload Response Ratio) reaches to a high value, and then the LURR decreases prior to the occurrence of

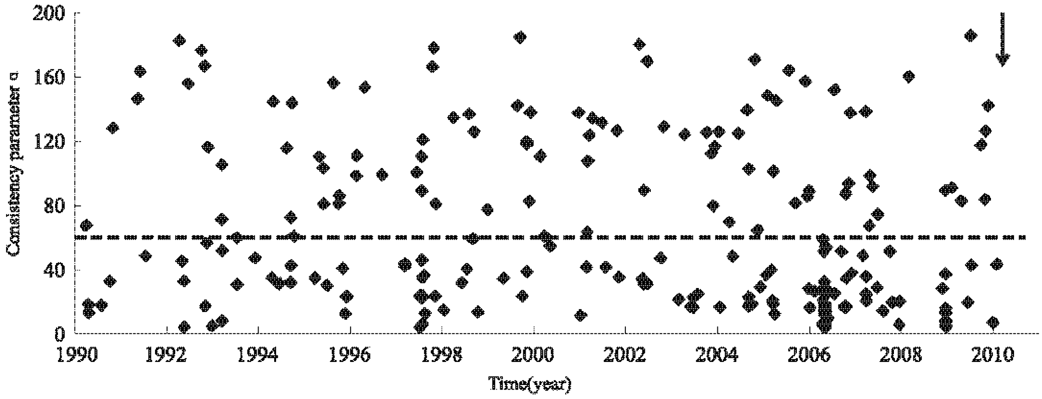
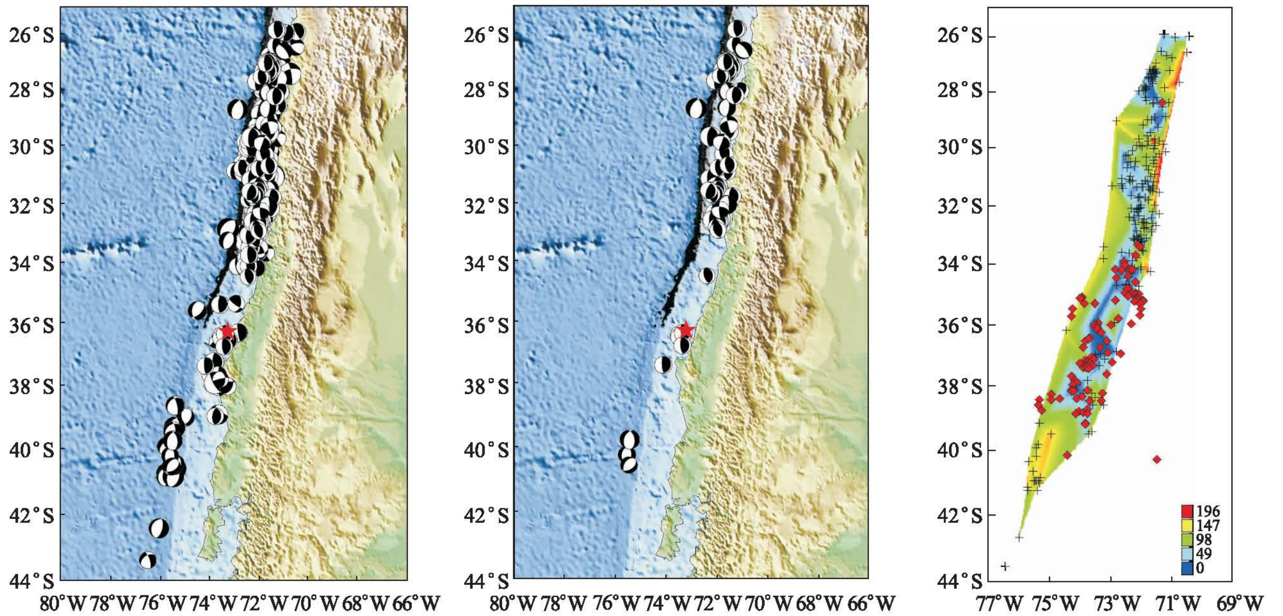


Figure 5 Variation of consistency parameter α of focal mechanism with time. The dashed line indicates 60° of consistency parameter and the arrows indicate the Mw8.8 earthquake



(a) All focal mechanisms

(b) The focal mechanisms from Jan. 5, 2006 to Jan. 30, 2010. (The red star indicate the main shock)

(c) Map of spatial interpolation of cons stency parameter of focal mechanisms and aftershocks of the *M*w8.8 earthquake (the red diamonds indicate aftershocks)

Figure 6 Map of focal mechanism and spatial interpolation of consistency parameter in central Chil subduction during different period

macro-fracture[23].

We interpolated the consistency parameter by TIN (Triangle Irregular Network) algorithm in MapInfo (Fig. 6(c)). There is a belt of lower values, which coincides with the main rupture area (34° – 38°S)[24] and the distribution of the aftershocks, based on visual inspection of the similarity between the pre-seismic locking and co-seismic slip distribution. Recent geodetic observations suggested this patchwork of locked zones, surrounded by creeping areas along the megathrust plate interface, hypothetically accumulates stress in the form of slip deficit in the interseismic period in a spatially heterogeneous pattern that is similar to future earthquake slip distributions[25].

4 Discussion and conclusion

The consistency parameter of CMT solutions shows lower value before the 2010 Maule earthquake. The area of lower value was visually coincided with the distribution of aftershocks and the main rupture area[24]. Recent seismology and geodetic observation suggest that stress accumulation in the interseismic period in a spatially heterogeneous pattern that is similar to future earthquake slip distributions.

Generally, the phenomenon should be test by time for its reliability. Acoustic Emissions (AE) recorded during four tri-axial compression experiments involving two types of rock specimens confirms that anomalously high LURR values and Accelerating Energy Release (AER) precede macro-fracture of the specimens[23]. In subduction zone, the plate motion makes stress accumulation in the interface between plates. When the stress reaches the failure limit, the area of slip deficit will slip. If it is considered that earthquakes are concentrated on the interface, the focal mechanism of these earthquakes should be consistent with one another along with the relatively stable plate movement. However, earthquakes generally occurred in a considerably wide region and there is a considerably large difference among them. They are relatively consistent with one another only under some special circumstances, such as the periods before and after great earthquakes, during this period the future large earthquake control the stress accumulation and the pattern of focal mechanisms. These earthquakes cannot be considered to concentrate on a pure fault surface, but are distributed in a certain volume. It may coincide with the rupture area of the future large earthquake.

Earthquake prediction is a difficult problem in earth science that the public wants it to be solved urgently, yet for achieving this scientific goal long-search is required. We obtained some information about earthquake preparation process from the convergence of stress field direction from focal mechanism of foreshocks and that from mainshocks before a large earthquake. The follow-up study on this research needs to consider this technology for selecting regions where earthquake precursor are obvious, so as to achieve possibly clearer information on foreshock's focal mechanism trending to that of the main shock.

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