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The May 10, 1994 earthquake: evidence of a seismic pre-slip in the northern Chile seismic gap?

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RESUMEN

Se analiza el hipocentro y el mecanismo focal del terremoto del 10 de mayo de 1994 (m_b=5.9). La profundidad y el mecanismo focal es obtenido usando las formas de las ondas P, SV y SH registradas en estaciones de periodo largo ubicadas a distancias telesísmicas. El epicentro fue obtenido mediante una determinación conjunta usando los tiempos de llegada registrados en redes locales y telesísmicas. El mecanismo focal obtenido corresponde a un fallamiento inverso de bajo ángulo, ubicado a 58 km de profundidad. El 8 de agosto de 1987 ocurrió un evento tensional (m_b=6.4) a una profundidad de 76 km; este evento y el evento compresional de 1994 están ambos localizados en el extremo norte del área de ruptura del terremoto de 1877, a aproximadamente 200 km de distancia de la fosa, cercano a la zona de transición de la parte desacoplada de la placa de Nazca en subducción. Considerando los últimos 32 años de información disponible, la ocurrencia de los terremotos de 1987 y 1994 ha sido inusual. Se sugiere que ambos eventos podrían estar asociados a un pre-deslizamiento sísmico que estaría ocurriendo en la parte más profunda del contacto sismogénico interplaca, en la brecha sísmica del norte de Chile, la que podría estar cercana a la etapa final de su ciclo sísmico.

PALABRAS CLAVE: Brecha sísmica, norte de Chile, ciclo sísmico.

ABSTRACT

The focal depth and the focal mechanism solution of the May 10, 1994 earthquake (m_b=5.9) were obtained using the long period *P*, *SV*, and *SH* waveforms of stations located at teleseismic distances. Its epicenter was determined by a joint determination using arrival times of teleseismic and local networks. The focal mechanism obtained by the body waveform inversion corresponds to thrust faulting occurring at a depth of 58 km. On August 8, 1987, a tensional event (m_b=6.4) occurred with focal depth of 76 km. Both this event and the 1994 compressional event are located in the northern edge of the 1877 rupture area at a distance of about 200 km from the trench, close to the coupled-uncoupled transition of the subducting Nazca plate. A cluster of compressional events with magnitudes 5.0 $\leq m_b \leq$5.3 is also reported herein. This cluster, located offshore and aligned with the 1994 earthquake in the direction of plate convergence, could be associated with one of the main asperities of the future great earthquake expected in northern Chile. The occurrence of the 1987 and 1994 earthquakes has been unusual given the last 32 years of available information, and suggests that they could be associated with seismic pre-slip occurring in the deeper part of the seismogenic interplate contact of the northern Chile seismic gap, which could be close to the end of its seismic cycle.

KEY WORDS: Seismic gap, northern Chile, seismic cycle.

INTRODUCTION

Northern Chile region has been characterized as a seismic gap. The last great earthquake occurred on May 10, 1877 with a magnitude M_w~8.8 (Lomnitz, 1971; Kelleher, 1972; Nishenko, 1985; Kausel, 1986; Comte and Pardo, 1991). The estimated rupture length of the 1877 earthquake is about 450 km and ranges from the south of Arica (~18.5°S) to the north of Antofagasta (~23°S) (Comte and Pardo, 1991; Díaz, 1992). The subduction process in northern Chile is controlled by the interaction of the young Nazca plate (~60 Ma, Mayes *et al.*, 1990) subducting beneath the South American plate with an average convergence rate of 8.4 cm/yr in a N77°E direction (DeMets *et al.*, 1990). These characteristics imply an interplate contact that is strongly coupled. There are no reliable historical documents previous to the 1877 earthquake that allow the estimation of recurrence rates in the northern Chile segment. However, the absence of large thrust earthquakes ($M_S \geq 7$) during this century suggests that northern Chile could be a mature seismic gap (e.g., Comte and Suárez, 1993).

Analysis of microearthquakes recorded by two seismic experiments carried out in the middle and in the southern edge of the 1877 rupture area indicates that the maximum depth of the seismogenic interplate contact is ~60±10 km (Comte *et al.*, 1992; Comte *et al.*, 1994a, 1994b). This value has been estimated from the bidimensional *P*-wave velocity models obtained for the region which show oceanic crust subducting until this depth, and it agrees with the maximum depth of the thrusting events observed in northern Chile (Suárez and Comte, 1993). Furthermore, the distribution of stresses along the subducting Nazca plate obtained from locally and teleseismically recorded earthquakes indicates that there is a change from tensional to compressional stress in the upper part of the subducted slab; the change occurs ~200-250 km from the trench at depths of ~60 km. Therefore, the maximum extent of the seismogenic interplate contact has been estimated at about 60 km in depth using independent methods.

On May 10, 1994 an earthquake occurred in northern Chile with magnitude m_b=5.9, located by NEIC (National Earthquake Information Center) at 19.5°S, 69.55°W, and

59 km depth. The centroid moment tensor solution reported by Harvard exhibits a low angle reverse faulting mechanism (strike=10°, dip=27°, rake=100°) located at a depth of 76 km at 20.2°S and 70.0°W. This earthquake was strongly felt in northern Chile. The distribution of the reported intensities (Figure 1) exhibits an incomplete pattern because this area of Chile has a low population density. However, the distribution shows higher intensities inland, indicating that the epicenter of this event is located inland, far from the coast. The hypocentral location of this thrust event, and the unusual occurrence of this type of event with magnitude $m_b \sim 6.0$ near the deepest edge of the seismogenic interplate contact, motivated the analysis of the 1994 earthquake and its relation with previously recorded events observed in the northern part of the 1877 rupture area.

ANALYSIS OF THE 1994 EARTHQUAKE

Waveform inversion

A formal inversion of the long period *P*, *SV*, and *SH* wave recorded at teleseismic distances was performed following the procedure described by Nàbelek (1984). The parameters of the best fitting double-couple point source, including the focal mechanism, centroid-depth, and source time function, were determined using six stations of the Global Digital Seismological Network, located at epicentral distances between 20° and 90°. The amplitude of the seismograms are equalized to a common instrument with a peak magnification of 1500, located at a distance of 40°. A compressional wave velocity of 6 km/s, Poisson's ratio of 0.25, and density of 2700 kg/m³ was found to be adequate. Attenuation coefficients (t*=travel time/space average Q) of 1s and 4s were assumed in computing the effect of the inelastic attenuation for the *P* and *S* wave, respectively.

The results of this inversion give a focal mechanism with strike=347°, dip=31°, rake=91° (Figure 2), similar to that reported by Harvard. However, the obtained depth of 58 km agrees better with the solution reported by NEIC. Although the azimuthal coverage of the reporting stations is poor, there is good agreement both between the observed and the calculated *P* and *pP* waveforms at all stations and between the observed depth phases in the *SH* and *SV* diagrams. Therefore, the estimated focal depth and the character of reverse faulting are both reliable.

Relocation procedure

The epicenter relocation of the May 10, 1994 earthquake was done following the process described by Dewey (1971) using the *P*, *pP* and *S* phases reported by the

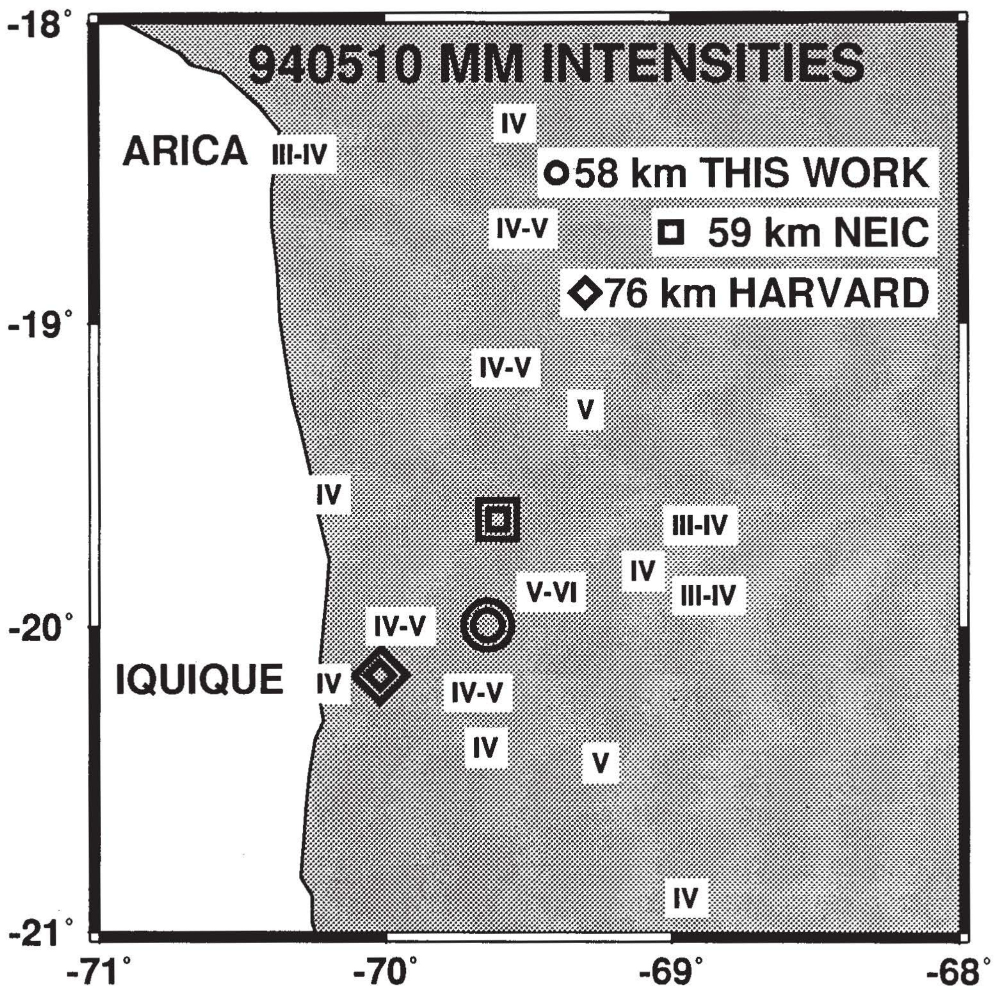

Fig. 1. Distribution of MM intensities of the May 10, 1994 earthquake. The locations of the epicenter reported by NEIC, Harvard, and that obtained in this work, are also shown.

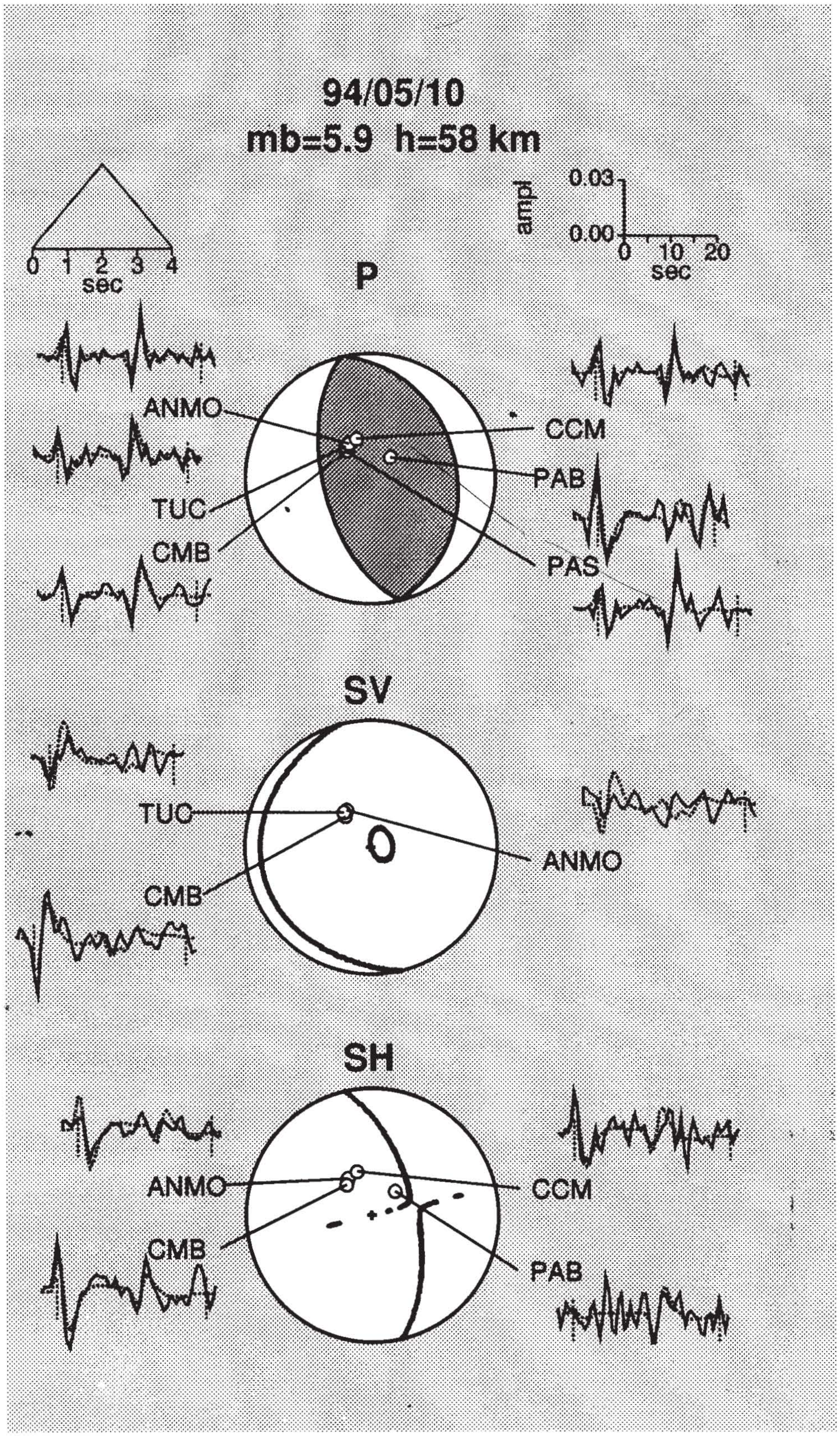

Fig. 2. Body waveforms inversion of the May 10, 1994 earthquake. The *P*, *SV*, and *SH* focal mechanisms are presented in a lower hemispheric projection. The continuous and dashed lines correspond to the observed and synthetic body waves, respectively. The source time function and the amplitude versus time scale are also given.

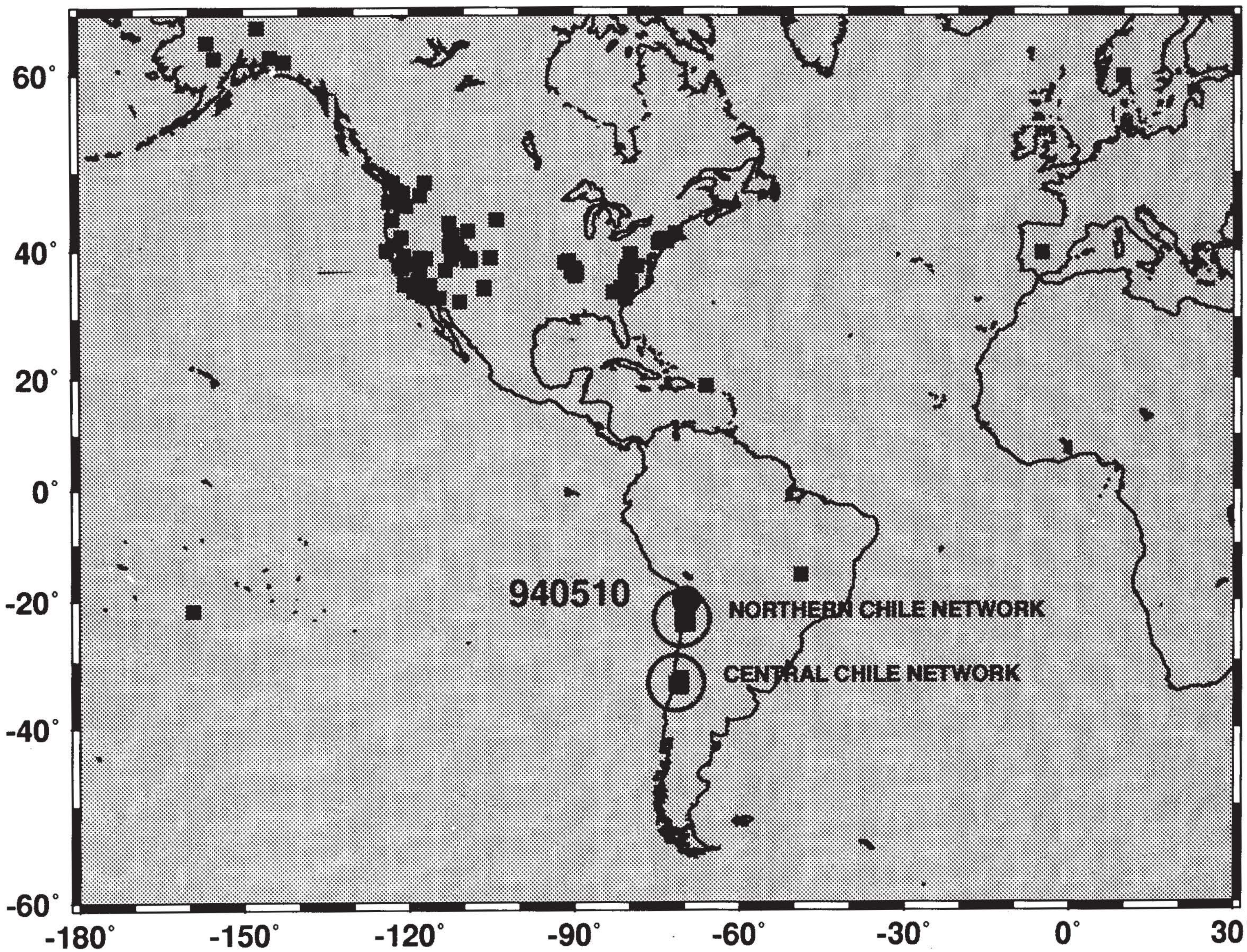

Fig. 3. Regional and teleseismic stations (squares) used in the relocation procedure. The epicenter of the May 10, 1994 earthquake is also shown (solid circle).

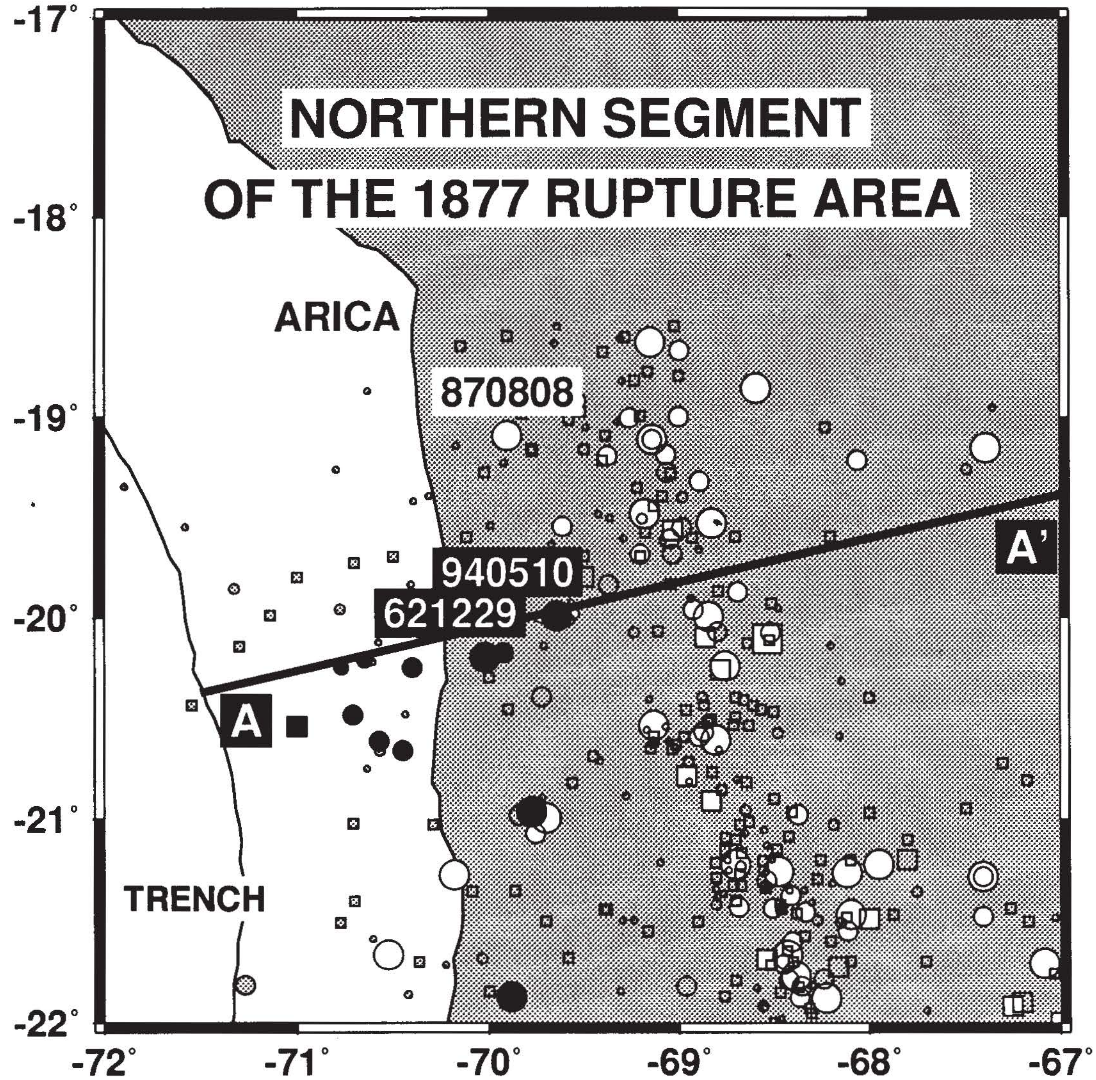

Fig. 4. Epicentral distribution of events with magnitudes m_b>5.0 recorded at teleseismic distances between 1963 and 1993. Circles and squares represent relocated and non-relocated events, respectively. Black, white, and gray colors represent reverse faulting events, normal faulting events, and events without reported focal mechanism, respectively. Size of the symbols is proportional to the magnitude. The location profile AA' oriented in the direction of convergence of the Nazca plate, is also shown.

International Seismological Centre (ISC) for 73 stations and the *P* and *S* arrivals of the Central and Northern Chile networks (Figure 3). The focal depth was fixed at the depth obtained in the inversion (58 km). The effect of the relocation is a southward shift of the epicenter given by NEIC of ~30 km; however, no significant changes in its longitude are observed (Figure 1). The major semi-axis of the error ellipse obtained from the relocation is about 15 km. Thus, this event is clearly located ~200 km from the trench.

SEISMICITY BETWEEN 1962-1994

Comte and Suárez (1995) performed a joint hypocentral determination (JHD, Dewey 1971) of the seismicity recorded at teleseismic distances between January 1962 and December 1991 with magnitudes $m_b \geq 5.5$. They also included in the analysis some urelocated events reported by NEIC which occurred between 1962 and 1991 ($5.0 \leq m_b < 5.5$), and between 1992 and 1994 ($m_b \geq 5.0$).

In that work, Comte and Suárez (1995) concluded that the southern part of the 1877 rupture area has been very active along the seismogenic interplate contact. Specifically, thrust events occurred on December 28, 1966 (m_b=6.6) and on March 3, 1987 (m_b=6.5); the latter event exhibiting strong aftershock activity. Further, on January 19, 1988 another low dip angle reverse faulting event occurred with magnitude m_b=6.3, and more recently, July 11, 1993, the last thrust event of this period occurred with a magnitude m_b=6.2. All of those events are located in the shallow part of the coupled region.

The northern part of the 1877 rupture area has been less active along its interplate contact than the southern part. Therefore, we will use the Comte and Suárez (1995), catalogue in the area included in a ±100 km wide slice centered at the epicenter of the May 10, 1994 earthquake (Figure 4) in order to analyze the role of this earthquake in the general behavior of this part of the northern Chile seismic gap.

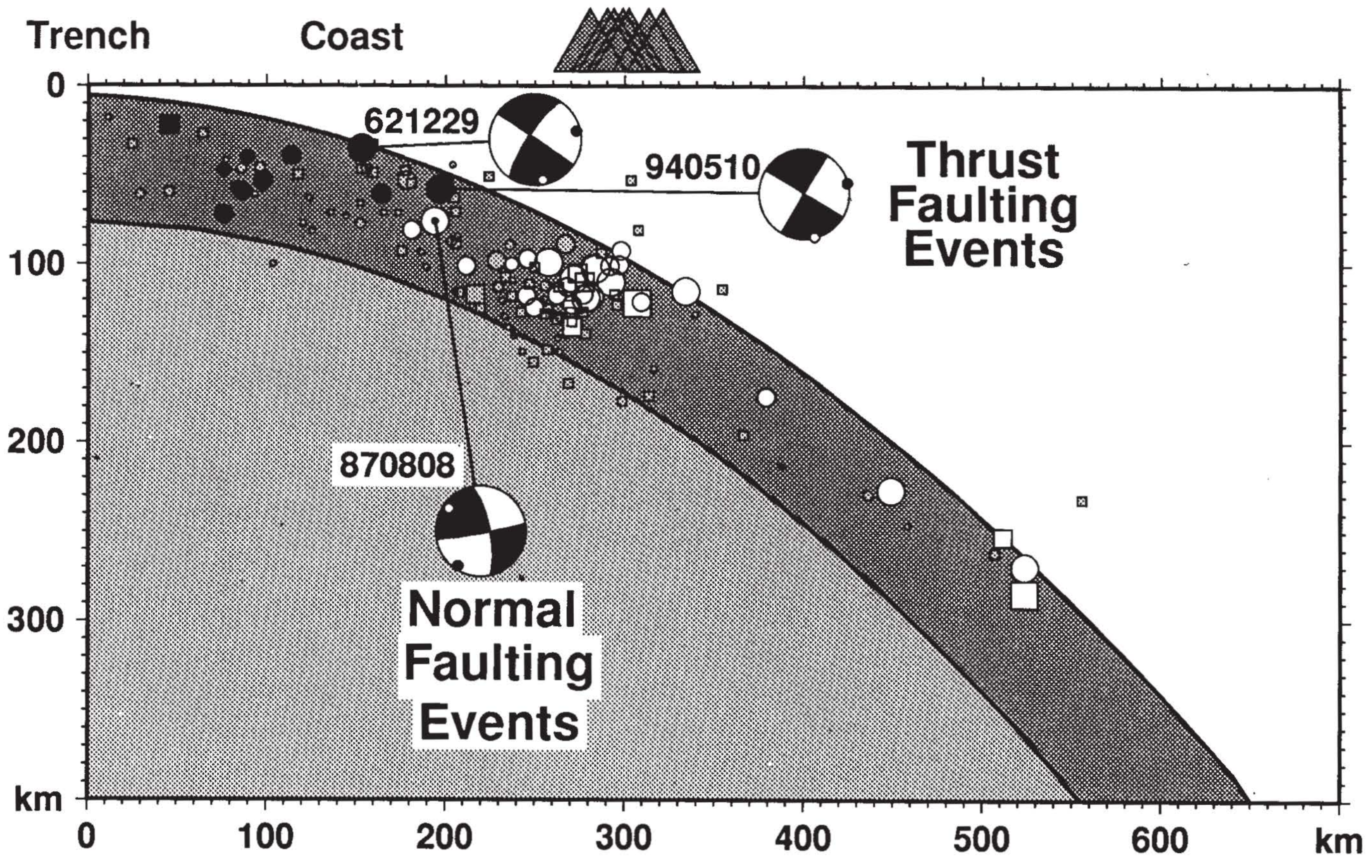

Fig. 5. Distribution of seismicity along profile AA' (see Figure 4 for profile location). The vertical lower hemispheric projection of the focal mechanism solutions (rotated in the same direction of the profile) are presented for selected events which are identified by their date of occurrence. Each focal mechanism shows the location of the P-axis (dark dot) and the T-axis (white dot). The origin at the trench, the location of the coastline, and the projection of the Quaternary volcanoes are also shown. The size and color of the symbols are defined in the caption of Figure 4.

The oldest event modeled by Comte and Suárez (1995) in the region close to the 1994 earthquake is the December 29, 1962 earthquake which is the only thrust event ($M_S \geq 6.5$) to have occurred in the northern end of the 1877 rupture area during the last 32 years. The depth of this event is 35 km and it is located at a distance of about 160 km from the trench. Since this event, this part of the gap was almost quiet for events with magnitude $m_b \geq 6.0$ until the occurrence of the tensional event of August 8, 1987 (m_b=6.4) located at a depth of 76 km. This event was also modeled by Comte and Suárez (1995) and is located about 200 km from the trench, which is roughly the same distance obtained for the 1994 event (Figure 4).

The distribution of this activity with depth is presented on Figure 5, which corresponds to a profile 200 km wide with respect of the 1994 epicenter, in the direction of plate convergence. In this figure it can be noted that the change from reverse to normal faulting events occurs at a distance of about 200 km from the trench, at ~60 km in depth. The depth of this change has been interpreted as the end of the seismogenic interplate contact. Therefore, the 1987 and the 1994 earthquakes occurred near the coupled-uncoupled transition in the place that had been almost quiet, at least for great events, during the last 32 years.

In the space-time diagram (Figure 6), it can be observed that between the 1962 earthquake and 1978, the seismogenic interplate contact was almost inactive. Since 1978, it has become active, generating reverse faulting events with magnitudes $5.0 \leq m_b \leq 5.3$. The locations of these events are clustered at distances less than 100 km from the trench suggesting a temporal migration toward the trench. The occurrence of the 1987 normal faulting event located at 76 km in depth and the 1994 reverse faulting event at 58 km in depth, suggest that the deeper part of the seismogenic interplate contact has been recently activated.

The southern part of the 1877 gap had been seismically more active during the last 32 years than its northern edge. However, around latitude 20°S, a cluster of seismicity is observed which has occurred since 1978 (Figure 4). This cluster of compressional events, aligned with the 1962 and 1994 earthquakes in the direction of plate convergence (N77°E), may be associated with the borders of one of the main asperities that will be broken in the next great earthquake occurring in northern Chile.

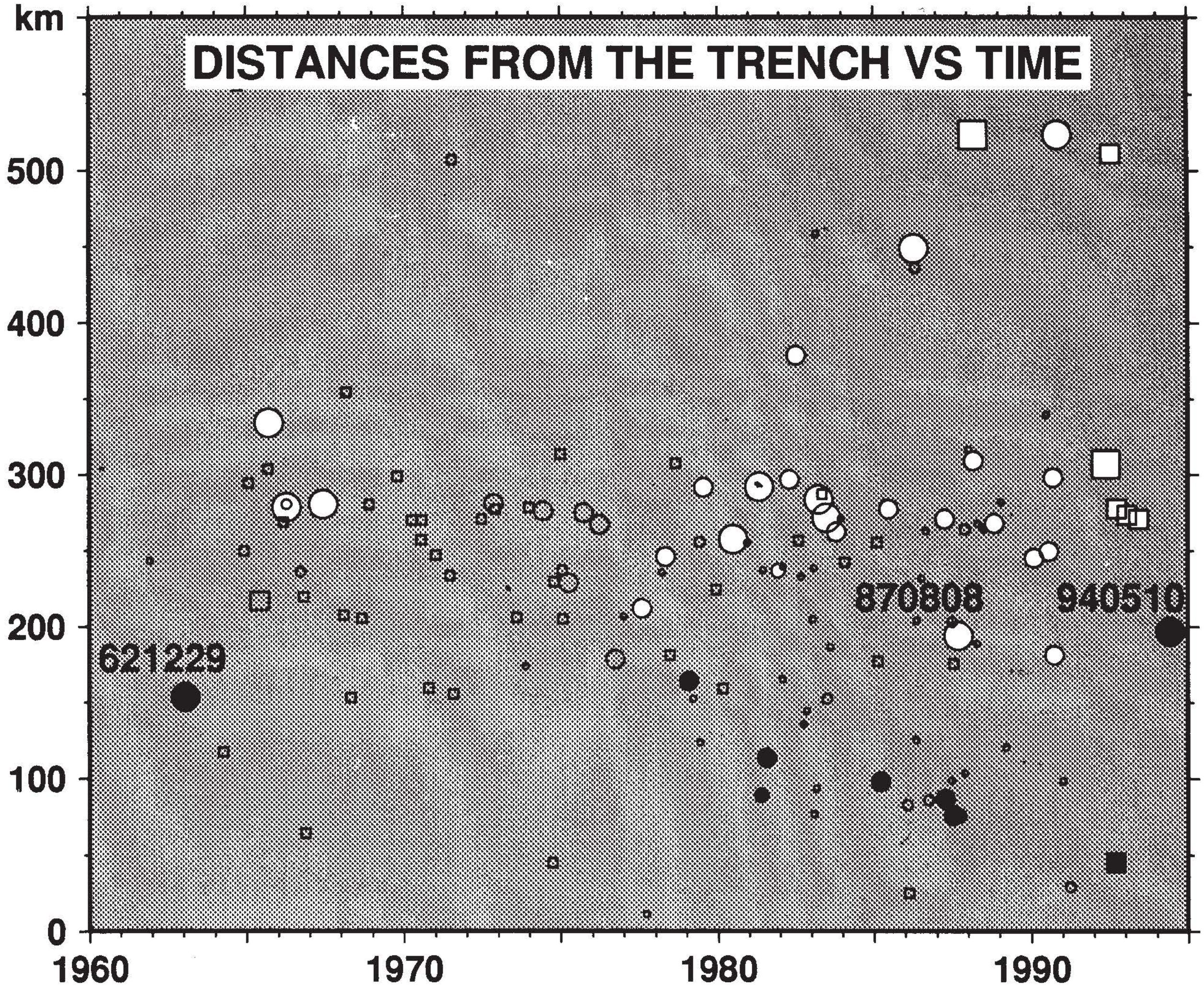

Fig. 6. Distances from the trench versus time diagram. The size and color of the symbols are defined in the caption of Figure 4.

We do not know if this behavior is representative of the last part of the seismic cycle in the northern Chile seismic gap, but we are sure that it is unusual given the last 32 years of observations.

CONCLUSIONS

The occurrence of the tensional event of August 8, 1987 (76 km in depth, m_b=6.4), and the thrust fault event of May 10, 1994 (58 km in depth, m_b=59), both of which are located near the coupled-uncoupled transition, may be associated with seismic pre-slip occurring beneath the seismogenic interplate contact in the northern Chile seismic gap. This may indicate that this gap is reaching the end of its seismic cycle. The cluster of low magnitude compressional events could be associated with one of the main asperities of the future great earthquake expected in northern Chile.

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